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NATIONAL COMMERCIAL GAS ASSOCIATION
UTILIZATION OF GAS APPLIANCES

PART I

ELEMENTARY PRINCIPLES OF COMBUSTION AND UTILIZATION OF ENERGY

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UNITS OF LIGHT AND ILLUMINATION AND PRINCIPLES OF LIGHT DISTRIBUTION

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TABLES AND GLOSSARY

BY

Robert ffrench Pierce

MEMBER OF BOARD OF EDUCATIONAL CONTROL AND CHAIRMAN OF COMMITTEE ON ILLUMINATION FOR PART 3 COURSE

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Elementary Principles of Combustion and Utilization of Energy

Robert ffrench Pierce

TO understand the production of heat by combustion, it is necessary to gain some knowledge of the simpler principles of chemistry.

All solids, liquids or gases are made up of one or more *elements*. An element is a substance that cannot by any known process be divided or split up into different substances. Substances which may be broken up into other substances of a different nature are termed *compounds*.

A compound differs from a mixture in that the latter may be separated into its component parts by physical means (filtering, sifting, or the like) and shows by its behavior the nature of these components. Thus, a mixture of sand and sugar will have a sweet taste, like sugar, a gritty feeling like sand, and particles of each may be detected by the microscope, and may be separated by washing out the sugar, which dissolves in water, leaving the insoluble sand behind.

The compound formed by the union of mercury (a silvery liquid) with chlorine (a greenish yellow gas) is a white powder (calomel) resembling neither of its components in any way, and the most powerful microscope is unable to show the slightest evidence of mercury particles.

A further difference between compounds and mixtures is that while mixtures may be composed of any proportions of substances, compounds are always formed of certain definite proportions. For instance, a mixture of oxygen and hydrogen may contain equal parts of each, or one part of oxygen to twenty of hydrogen, or any proportion between these, or any other proportion. A given *compound* of oxygen and hydrogen will always contain the same proportions. Water, for instance, always contains two parts or two volumes of hydrogen to one part or volume of oxygen. If two parts of hydrogen be

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burned in the presence of one and one-half parts of the oxygen, the hydrogen will combine with one part of oxygen forming water leaving the other one-half part as free oxygen.

For the purpose of making calculations concerning chemical compounds, it is convenient to make use of certain assumptions as to the nature of their composition.

This is necessary because chemistry deals with quantities of matter so small that they cannot be seen under the most powerful microscope, nor measured by the most delicate instruments. Since, however, the results of calculations based upon these assumptions are found to be in entire accordance with the results of actual experiment, these assumptions are just as useful and reliable as though they were demonstrated facts.

The first assumption made for purposes of calculation is that

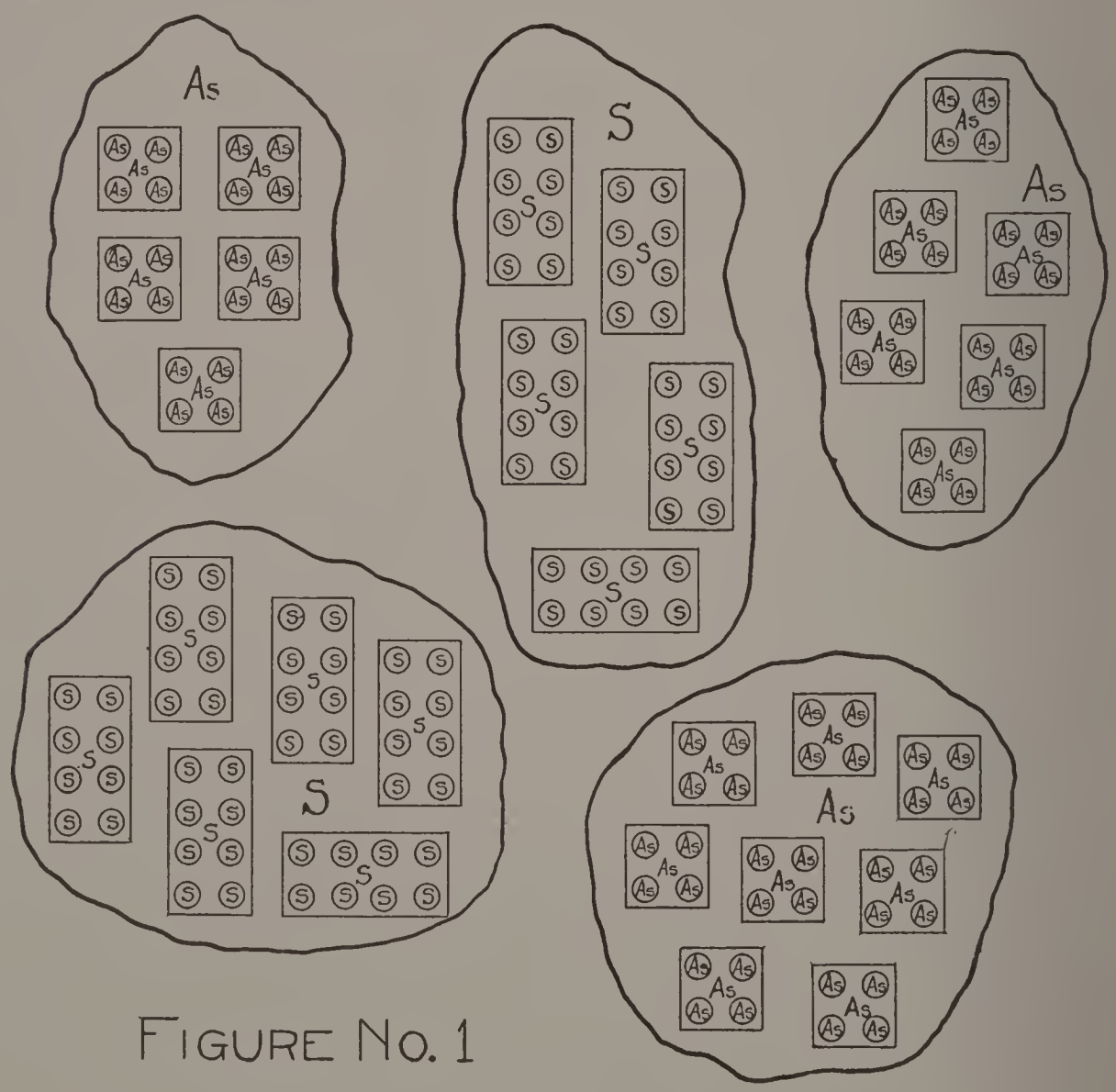


FIGURE No. 1

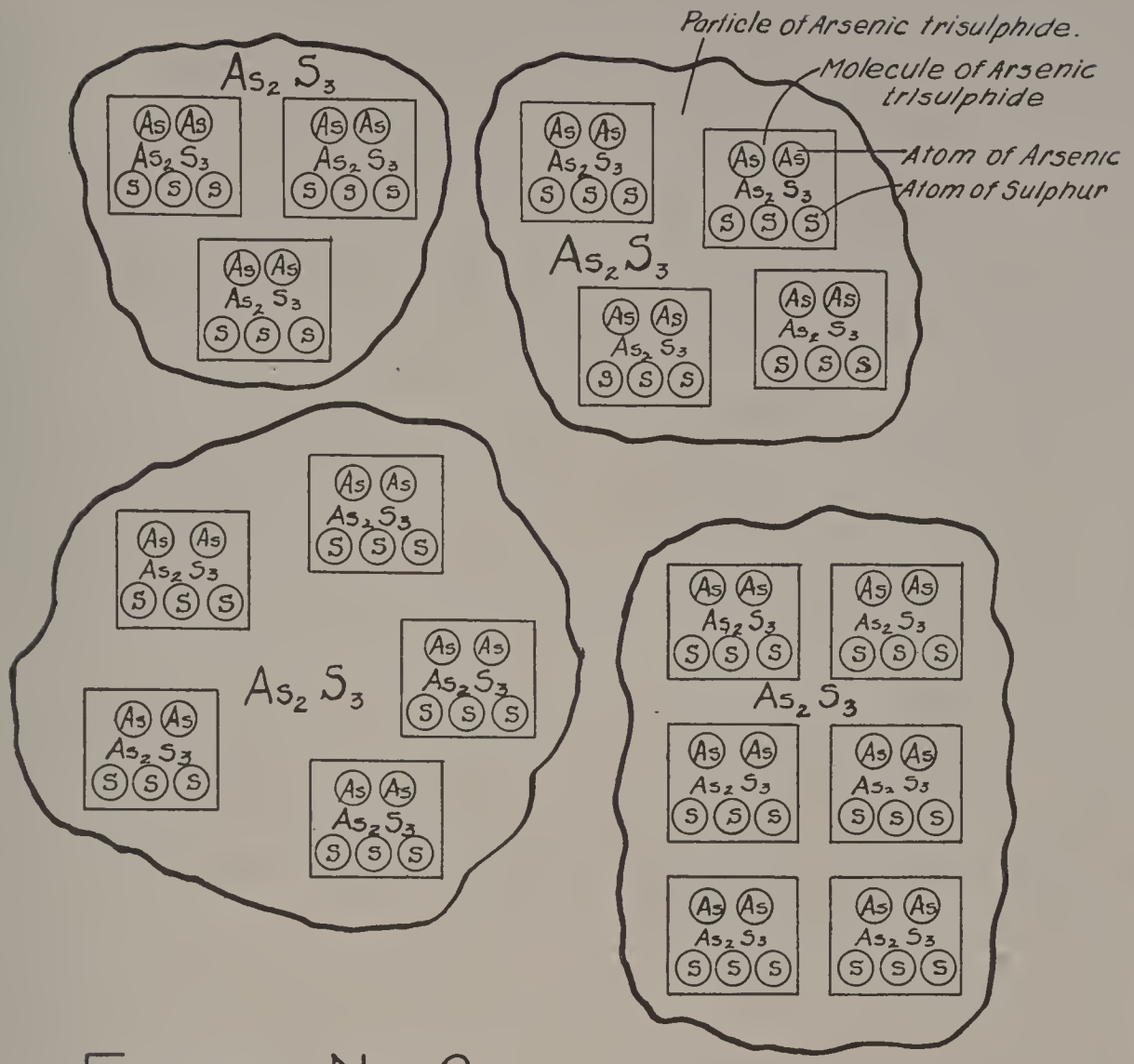


FIGURE No. 2

every compound or element is composed of extremely small particles called *molecules,* each of which is exactly like every other one (in the same element or compound), and these molecules are the smallest portion of matter that can exist by themselves (not joined with other portions of matter). Each molecule is made up of *atoms* which are regarded as the ultimate or indivisable portions of elements. Atoms cannot exist alone but immediately combine with other similar or different atoms to form molecules.

This may be shown diagrammatically. In Figs. 1 and 2 the large irregular areas represent small particles, the squares represent molecules, and the circles atoms.

Fig. 1 represents a *mixture* of arsenic and sulphur, the arsenic particles, molecules and atoms being designated by As and the sulphur by S.

Fig. 2 represents a *compound* of arsenic and sulphur—arsenic trisulphide, designated by the symbol As_2S_3, indicating the elements entering into its composition and their proportions (two parts of arsenic—As, to three of sulphur—S).

The differences between the mixture and the compound of the same elements are apparent.

In the mixture not all the particles and molecules are alike. There are particles of arsenic and particles of sulphur, molecules of arsenic and molecules of sulphur. In the compound, however, all the particles and all the molecules are alike. That is, the mixture of arsenic and sulphur contains particles of arsenic and particles of sulphur, while the compound contains no particles of arsenic or of sulphur, but only particles of arsenic trisulphide (As_2S_3).

This representation is only diagrammatic, and intended to show the manner in which we may suppose these particles to be arranged. The number of molecules in even the smallest visible particle of matter may run into the millions. For instance, one cubic inch of air contains 422,000,000,000,000,000,000 (422 million, million, million) molecules. (The counting of molecules is done by mathematical means by which we are able to count the number of these exceedingly small bodies to the same degree of accuracy as we may take a census of population.

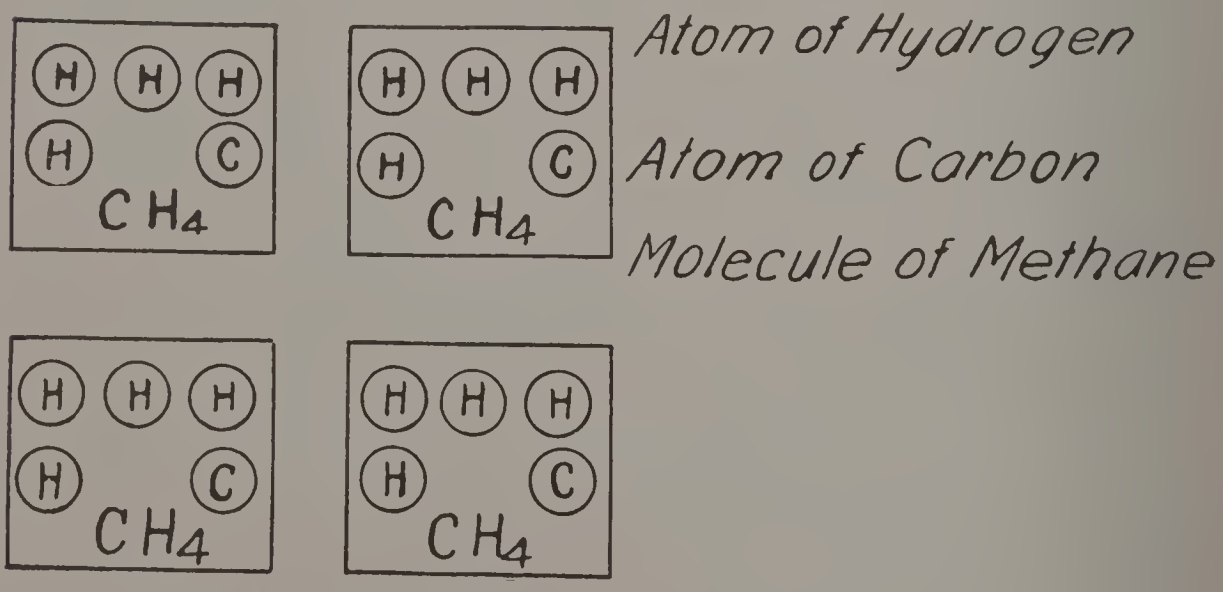


FIG. 3.

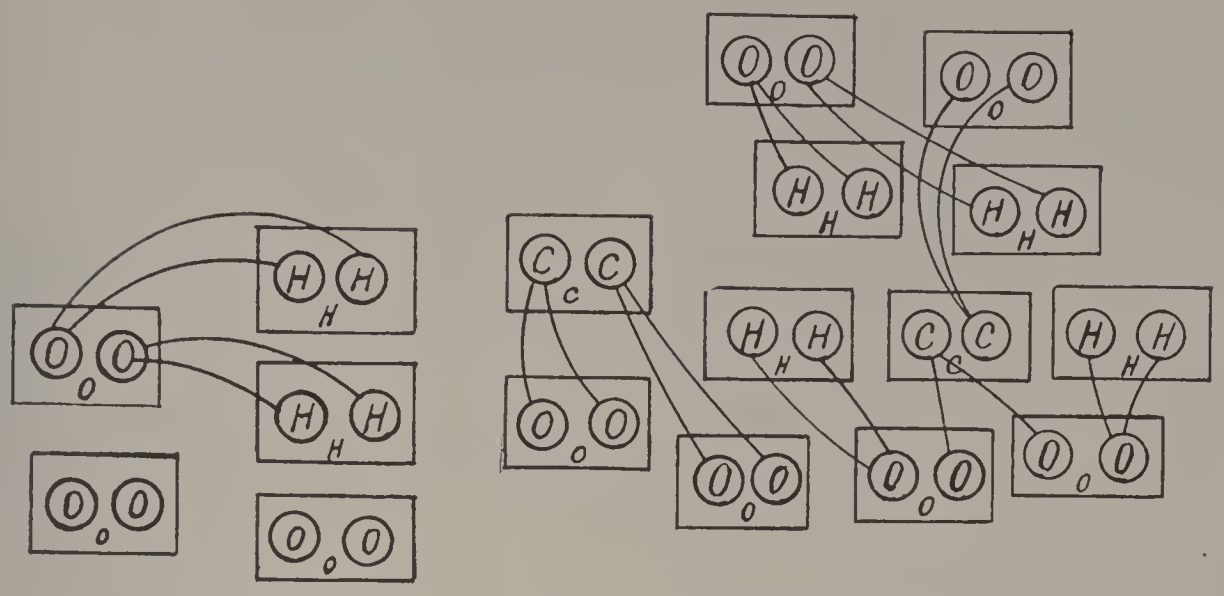


FIG. 4

To understand how chemical changes such as take place in the burning of gas produce heat, it is necessary to consider each atom as possessing within itself an attractive force for other atoms, and this is of a different degree for different kinds of atoms. For instance, under certain conditions, the attraction between hydrogen and oxygen atoms is greater than that between carbon and oxygen atoms.

This chemical attraction produces the tendency for atoms to combine and form different chemical compounds. The manner in which chemical compounds are formed may be illustrated by considering the combustion of methane (CH_4—one part carbon and four parts hydrogen). This gas is the principal constituent of natural gas of which it composes from 90 to 98 per cent., and is an important constituent of coal and of carburetted water gas. It is diagrammatically represented in Fig. 3, in which the squares represent molecules of the gas, and the circles atoms of its constituent elements.

When a sufficient degree of heat is applied to raise this gas to the ignition temperature, or burning point, the heat, which tends to expand and drive apart the atoms, finally breaks up the molecular structure, and for an instant the molecules may be regarded as broken up, the atoms being free, that is, not combined into molecules. Since, however, atoms cannot exist in a free

state (the *molecule* being the smallest particle of matter that can exist in this state), the atoms instantly seize upon each other to form new combinations. Thus the carbon atoms combine to form carbon molecules, while the hydrogen atoms form molecules of hydrogen. The carbon molecules gather together into particles, and these are raised to incandescence (become *light-giving*) by the heat of the flame, and produce the luminosity which characterizes the open gas flame. Both carbon and hydrogen pass rapidly to the outer surface of the flame, where the hydrogen combines with the oxygen of the air (Fig. 4), forming water vapor (H_2O), while the carbon combining with the oxygen forms carbon dioxide CO_2 (Fig. 5).

If, however, a plentiful supply of oxygen is well mixed with the methane before combustion takes place (as in a Bunsen flame) the combining of the carbon and the hydrogen with oxygen is practically instantaneous and the formation of carbon particles does not take place, hence, the lack of luminosity in the Bunsen flame.

The relation of heat to these chemical changes may be illustrated by the well-known fact that the striking together of bodies produces heat. For instance, the repeated blows of a ham-

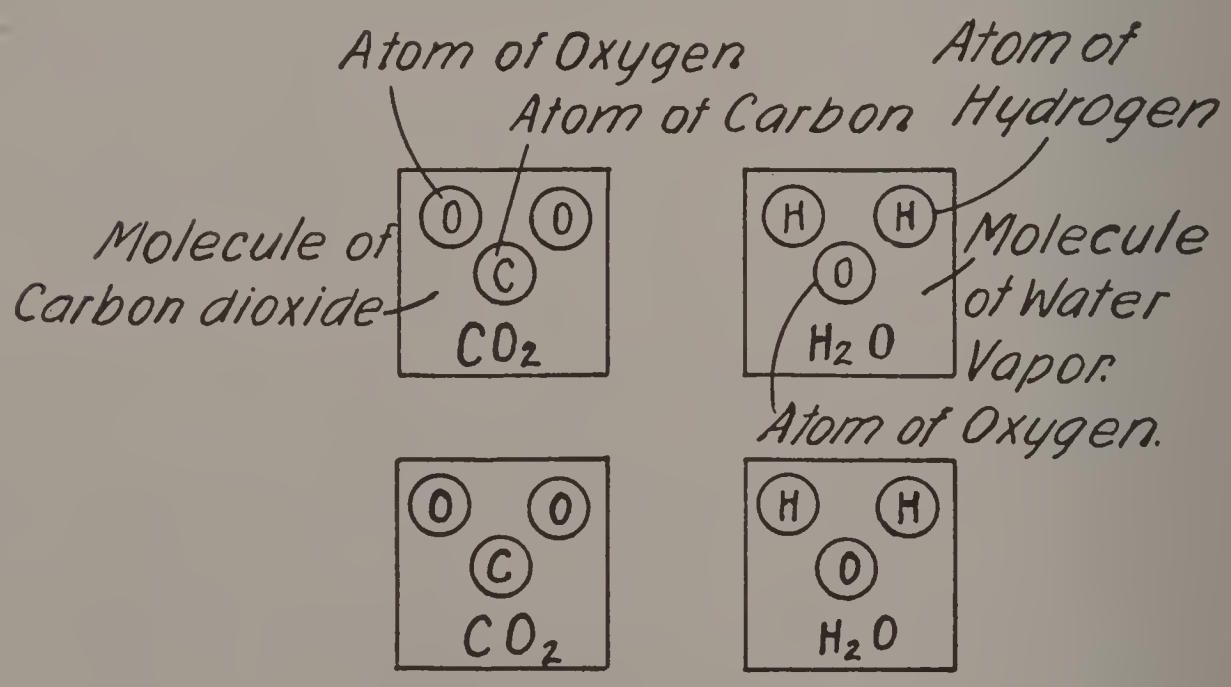


FIG. 5.

mer upon a piece of iron will, if sufficiently vigorous and rapid, in time *produce* enough heat to raise the iron to red heat. On the other hand, heat is *required* to expand or separate bodies. To drive molecules of water apart and expand it into steam, it is necessary to supply heat to the water. In a similar way the tearing apart or breaking up of a molecule requires heat to be furnished to it, while the rushing together of molecules to form compounds produces heat.

In order to raise methane to the burning or ignition point (the temperature at which its atoms of carbon and hydrogen will be driven apart) a certain amount of heat is required, hence the necessity of the lighted match, electric spark, glowing platinum or pilot flame. After the molecules are broken up, however, their atoms combine anew with the oxygen of the air, and the rushing together of the atoms to form these new combinations produces sufficient heat to break up the incoming methane, and thus keep up the combustion, in addition to producing heat for useful purposes.

Thus there are two kinds of chemical reactions—heat-producing, called *exothermic,* and heat-requiring or heat-absorbing, called *endothermic*.

The heat produced by exothermic reactions is the result of the rushing together of the atoms of the gas during their conversion into new compounds. It should be borne in mind that the distinction between endothermic and exothermic reactions does not depend upon whether a given compound is *formed* or *broken* up, but upon whether the reaction *produces* heat or *absorbs* heat. The *breaking up* of methane into carbon and hydrogen, and the *forming* of calcium carbide by the union of calcium (lime) and carbon in the electric arc are both endothermic reactions, requiring heat to produce them. On the other hand the *formation* of water vapor by the union of hydrogen and oxygen is an exothermic reaction *producing* heat. In the gas flame, both endothermic and exothermic reactions are going on at the same time and it is the *excess* of heat produced by the exothermic reactions over that required for the endothermic reactions that is available for doing work.

A combustible gas is therefore a carrier of energy, which may under proper circumstances be converted into heat.

For this reason, the quality of a gas (as far as usefulness for producing heat is concerned) is best expressed by the amount of heat which may be extracted from it.

Heat is entirely different from temperature. Adding heat to a body does not always increase its temperature, though the unit by which heat is measured (the British Thermal Unit or B. T. U.) is defined as the quantity of heat which will increase the temperature one pound of water one degree Fahrenheit from 62 degrees (abbreviated 62°). But while one B. T. U. will raise the temperature of one pound of water from 62° to 63° Fahr., nearly 1,000 B. T. U.'s may be added to a pound of water at 212° Fahr. without raising its temperature in the least. This is because at 212° Fahr. water at atmospheric pressure turns into steam at the same temperature, and this conversion uses up a large amount of heat. This heat is called "latent heat of vaporization." Furthermore, different substances show different increases in temperature when supplied with the same quantity of heat, and with each substance the increase may vary according to the temperature. The quantity of heat required to raise one pound of any substance one degree Fahr. from any particular temperature is called the Specific Heat of the substance at that temperature.

Substances differ not only with regard to their capacity for absorbing heat, but also in the readiness with which they transmit or conduct heat, and in order to design gas appliances, or to select or use them intelligently it is necessary to take all these things into consideration.

The principal consideration in the design and operation of gas-burning appliances is the production of the highest practicable temperature in the flame itself. This is particularly true of incandescent gas lamps, and is of very great importance in nearly all gas-burning appliances.

The flame temperature determines the efficiency of the appliance, other things being equal. For instance, suppose we wish to maintain a melting-pot at a temperature of 500° Fahr.

Since heat cannot flow except from a body of higher to one or lower temperature, all the heat in the gases below 500° is wasted, while that above 500° is practically all available for maintaining the temperature in the pot. Now, if the temperature of the flame be 1,500°, one-third of the heat represents

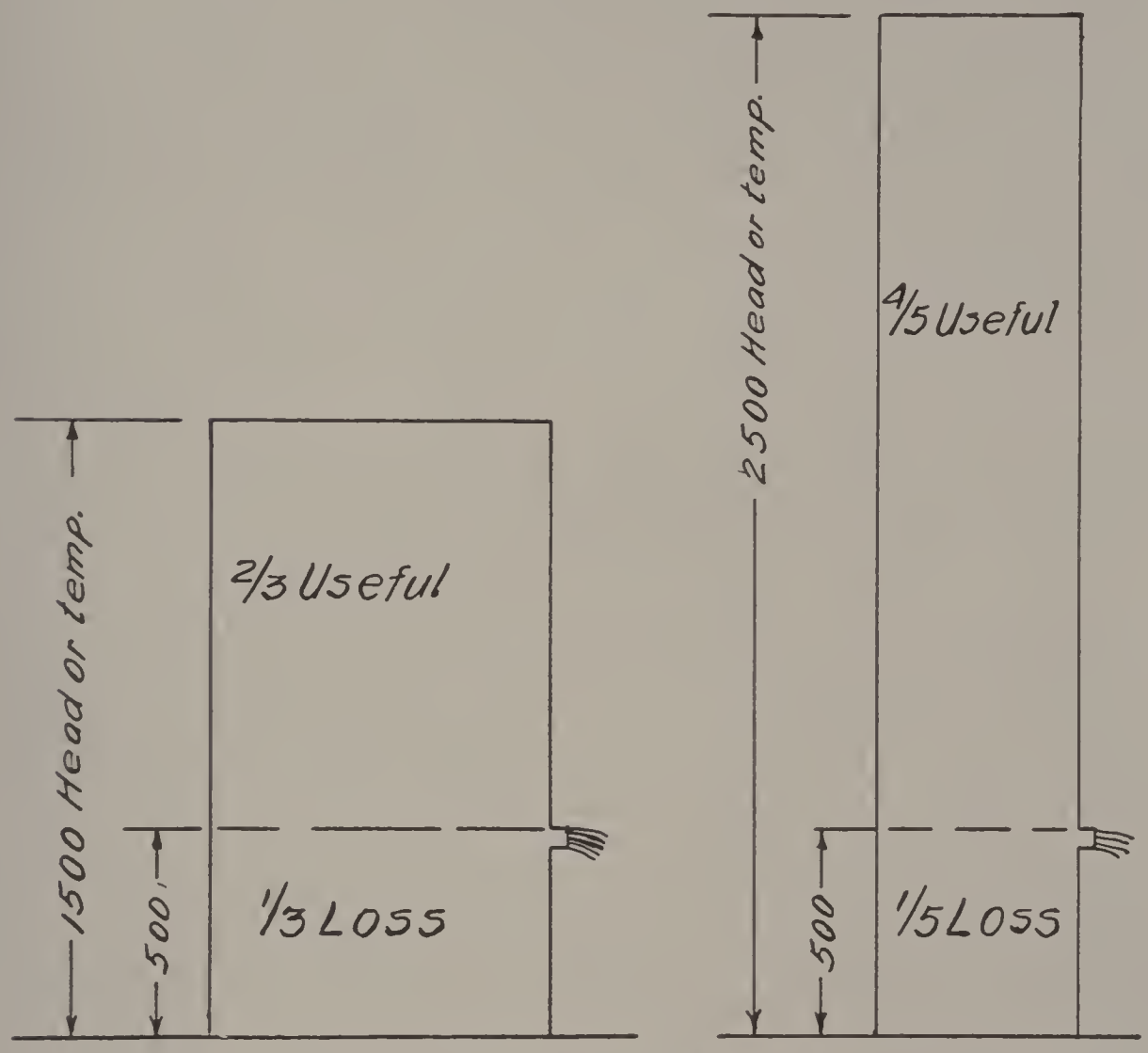


FIG. 6

temperatures below that of the metal, and hence useless, while two-thirds of the heat is available or useful. If, however, we increase the temperature of the flame to 2,500°, then only one-fifth is wasted, while four-fifths is useful. This is illustrated diagrammatically in Fig. 6.

Just as water can flow only from a higher to a lower level,

heat can flow only from a body of a higher to one of a lower temperature. If water is to be discharged at a 500-foot level, only sources *above* that level are available unless mechanical means, such as pumping, are utilized. If it is desired to add heat to a body already at 500 degrees, it must be brought in contact with substances of higher temperature. As soon as these substances are cooled to 500 degrees by contact with the heated body, they must be rejected and the heat in them is wasted as far as this particular process is concerned.

Thus, the efficiency of an appliance depends to a great extent upon providing proper conditions of combustion for the maintenance of high flame temperatures. For each adjustment of a Bunsen burner there is one gas pressure and gas composition at which the highest flame temperature will be reached. If this is disregarded and variations of pressure are permitted at the customer's burners, and if gas of varying composition be supplied, even though the candle-power and heating value (B. T. U.) of the gas remain the same, loss in efficiency will occur.

Table I shows the variations in gas consumption and in light-giving power (which is an indication of temperature) in an inverted incandescent gas lamp. In this table Column 1 gives (in inches of water column) the limits between which the gas pressure varied. Column 2 gives the increase in consumption resulting from raising to the *upper* limit the pressure upon a lamp adjusted for the *lower* limit. Column 3 gives the decrease in light output resulting from dropping to the *lower* limit the pressure upon a lamp adjusted for the *upper* limit.

TABLE I

Col. 1	*Col. 2*	*Col. 3*
2 —2½	13%	13%
2½—3	9	11
3 —3½	8	6
3½—4	7	8
4 —4½	6	3
4½—5	6	6

Col. 1	*Col. 2*	*Col. 3*
2 —3	22	20
3 —4	17	10
4 —5	14	11
2 —4	48	26
3 —5	30	13
2 —3½	34	24
3 —4½	24	18

It is the occasional variations in the composition of the gas that are responsible for the housewife's complaint that the gas is "poor" on certain days. It may be entirely up to the legal standard as to candle-power and heating value, but if it is of different composition from the gas on which the burner was adjusted, it will fail to do efficient work in the lamp, oven or water-heater.

The temperature of the open flame is necessarily low. The flame tends to spread or extend out until it comes in contact with enough oxygen to consume the carbon and hydrogen in the gases. This produces a flame having a large surface.

Just as water will flow more rapidly through a large pipe than through a small one, so heat will escape more rapidly from a large surface than from a small one. As the temperature of the flame is due to the heat in its gases, the more rapidly this heat is lost the lower the temperature of the flame.

The smaller the flame in which a certain amount of gas may be burned the greater the flame temperature, and to reduce the volume or size of the flame, it is necessary to furnish oxygen more rapidly at the place where combustion is taking place, so that it will not be necessary for the flame to spread out so far in order to encounter enough oxygen to consume its gases.

In the Bunsen burner, which is, broadly speaking, the type used on every modern gas burning appliance (except reflector-type room heaters), the gas issues in a thin stream from a small orifice (Fig. 7) surrounding which are air-ports—through which the *primary* air required for the combustion of the gas is drawn by the velocity of the gas stream. The air so drawn in or *entrained* is called *primary air* because it is the first air to

be mixed with the gas. The balance of the air required for combustion is obtained from the air surrounding the flame and is termed *"secondary air."*

#6 Reflex Lamp

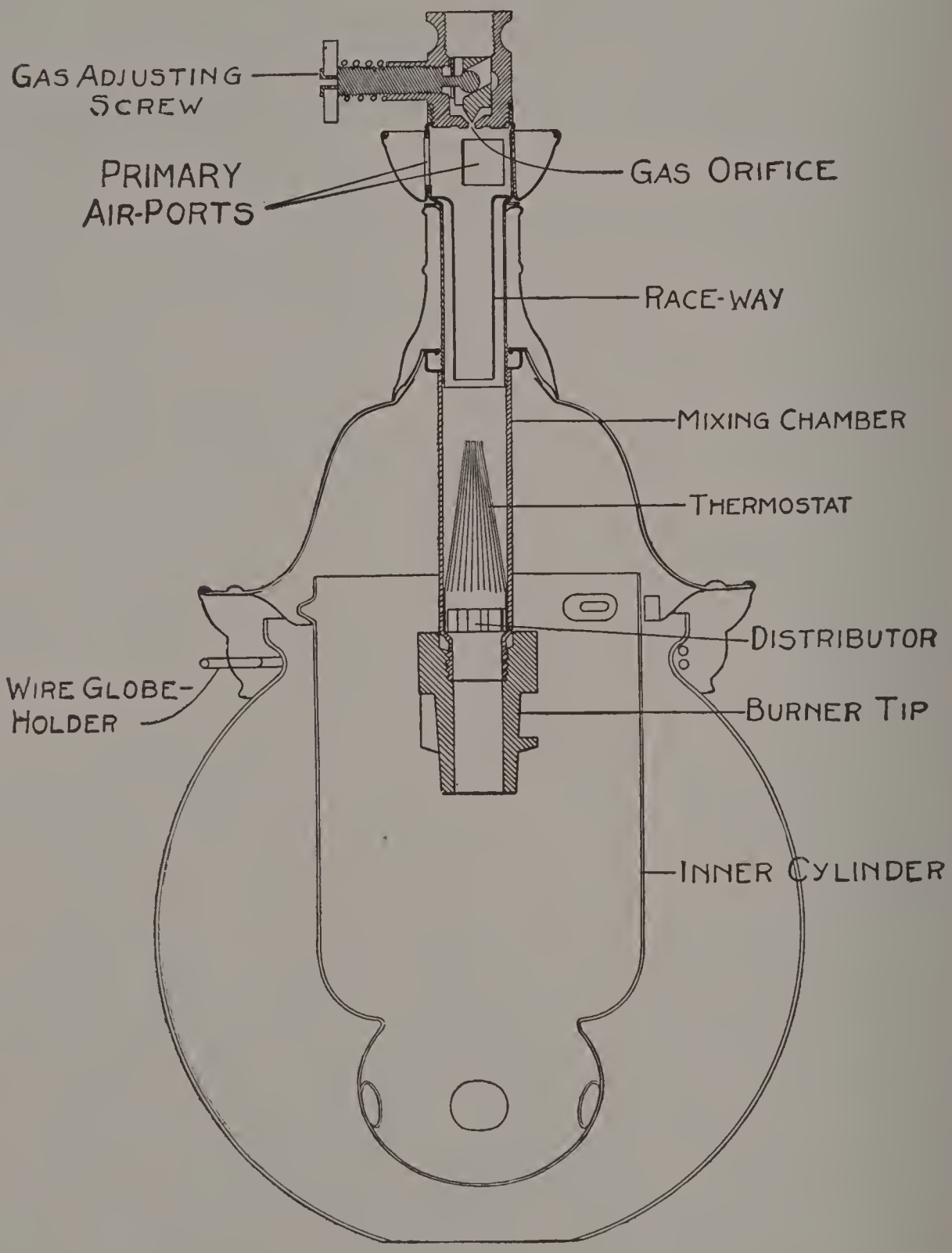


FIG. 7

The action of the gas in entraining primary air depends upon the friction of the gas-stream against the surrounding air. The particles of air next to the gas-stream are swept along with it into the mixing chamber. Other particles rush in to take the empty places, and thus a steady flow of air through the air-ports, along the gas-stream and into the mixing chamber is secured. The gas and air mix more or less thoroughly in the mixing chamber—and the mixture is ignited at the nozzle or burner tip. There being nearly or quite enough oxygen in the mixture to consume the gas, combustion takes place rapidly in a very small space, and a high temperature is produced.

If the amount of oxygen (or air) be less than that necessary for complete combustion, the balance (called *secondary air*) is taken from the air surrounding the flame. If the mixture is greatly deficient in oxygen the unconsumed gases will burn outside the conical flame—in much the same manner as the gas from an open flame tip, and with the same yellow luminosity.

The presence of this yellow portion in a Bunsen flame is therefore evidence that insufficient air is being drawn in or entrained through the air-ports.

The size of the flame for a given volume of gas consumed will depend upon the velocity of the outflowing mixture and the quantity of air present in the mixture.

There are limits, however, to the increases in flame temperature that may be obtained by increased entrainment of air. Wherever a mixture of gas and air flows into a flame there is a tendency for the flame to travel back along the outflowing stream of this mixture. This tendency is opposed by the velocity of the mixture itself, and when a balance is reached the flame remains stationary.

The speed with which the flame will travel through a still mixture of air and gas depends upon the proportions of gas and air present. The greater the proportion of air (up to that required completely to consume the gas) the greater the speed of the flame.

At the low pressures ordinarily in use it is impossible to entrain all the air necessary for combustion because the speed

with which the flame travels back toward the orifice is greater than the velocity of the issuing mixture. At higher gas pressures, however, the velocity of the mixture is increased, and at certain pressures a sufficient velocity may be secured to permit the entrainment at the orifice of all the air required for combustion, without danger of the flame traveling back to the orifice. Also a more perfect and intimate mixture of the air and gas is secured due to the high velocity and consequently violent agitation at the point of mixture. Since the temperature of a flame (for a given quantity of the gas) depends upon the smallness of the flame, and this latter depends upon the proportions of air and gas and the uniformity of the mixture, it is evident that the efficiency of a burner will depend (1) upon the pressure of the gas at the orifice, (2) upon the pressure of the air at the *primary* air-ports, and (3) upon the design of the Bunsen tube (with reference to entraining air and producing a perfect uniform mixture).

In the ordinary atmospheric burners (those in which no air under greater than atmospheric pressure is used) the third consideration will be of the greatest importance, since the gas pressure limits are usually fixed by service conditions. If, however, the burner be turned down at the key, or the service cock at the meter be partially closed, the appliance will not receive the full service pressure, the flame temperature will be lowered and more gas will be required to perform a given work.

In particular appliances certain considerations other than the production of maximum flame temperature must be taken into consideration. These will receive attention under the lessons dealing with individual appliances.

The relations which conditions of gas service bear to the performance of appliances will also vary with the particular appliance under consideration. The following general statements, however, hold good with reference to all appliances.

GAS PRESSURES.

With gas of a given quality the velocity of flow through the orifice will depend (1) upon the pressure; (2) upon the form

of the orifice. The higher the pressure, the greater the velocity of the issuing jet, and accordingly the greater the volume of gas passed during a given time. If the pressure be increased, the greater volume of gas passed will require a proportionately greater volume of air in order to maintain perfect combustion and the same flame temperature. The increased velocity of the jet enables it to entrain a greater quantity of air, but *not* in direct proportion to the increased quantity of gas flowing. The quantity of gas issuing is proportional to the velocity; that is, if the velocity be doubled, the quantity of gas passed will also be doubled. The amount of air entrained, however, is proportional to the *square* of the velocity. That is, if the velocity of the issuing gas be doubled ($2\times2=$) 4 times as much air will be entrained. If the velocity be tripled ($3\times3=$) 9 times amount of air will be entrained. This increased air results in a tendency for the flame to travel back, which is opposed, however, by the increased velocity of the mixture of gas and air issuing from the nozzle. If the Bunsen tube be so arranged that the increased amount of air has no opportunity to become uniformly mixed, a roaring sound will be produced. This trouble may be corrected (1) by reducing the air supply by partially closing the air-shutter (when present) or (2) by interposing gauzes or similar obstructions in the mixing chamber. These serve two purposes. In the first place by obstructing the mixing chamber, they tend to oppose the entrainment of air, and thus reduce the excess. Furthermore, they tend to correct momentary tendencies to "flash back" by conducting the heat away from the flame and reducing the temperature of the gases below the ignition point. When the flame travels back to the gauze at frequent intervals, a "popping" sound occurs which is a symptom of excessive primary air.

If, on the other hand, the gas pressure at the orifice be reduced, less gas will pass and insufficient air will be entrained. If the velocity of the gas be reduced to one-half, the amount of air entrained will be reduced to one-fourth. This will produce lower flame temperature, and in some cases incomplete

combustion (evidenced by a yellow flame tip and in incandescent lamps carbonized mantles).

This may be corrected (1) by a wider opening of air-ports; (2) by removing gauzes or substituting one of larger mesh in the mixing chambers.

SPECIFIC GRAVITY.

Specific gravity is a measure of the weight of a gas. It is expressed by the ratio between the weight of a certain volume of gas and the same volume of air. If one cubic foot of a gas weighs one-half as much as one cubic foot of air the "gravity" of the gas is said to be one-half or as always expressed in figures—.5.

The specific gravity of gases varies according to their chemical constituents and the proportions of the latter. The specific gravity of typical coal gas is only about two-thirds that of typical carburetted water gas, and the specific gravity of both carburetted water and coal gases will vary if the processes of manufacture are not uniform, and if means are not taken to avoid changes in composition through the "dropping out" of illuminants in distribution to the consuming premises.

The "illuminants" (see Glossary) are heavy vapors which are readily carried by the non-illuminating gases at ordinary temperatures and pressures, but less readily at lower temperatures and higher pressures, under which conditions they drop out more or less completely. If for any reason the pressure of a gas is increased or its temperature lowered, a portion of the illuminants come down as liquids and collect in the pipe, and the remaining gas is thus of different composition.

The effect upon the burner of varying specific gravity is somewhat similar to that of varying pressure, and often far more pronounced. The lighter the gas (the *lower* its specific gravity) the greater the velocity of the jet issuing from a given orifice and the greater the volume of gas passed during a given time. As the change in specific gravity is accompanied by a change in chemical constitution, the amount of air required for

combustion is also changed. Coal gas requires more air for combustion than does carburetted water gas; therefore, if in a burner properly adjusted for a certain mixture of coal and carburetted water gas, the proportion of coal gas be increased, insufficient air will be entrained, and low flame temperature or incomplete combustion will ensue. If the proportion of water gas be increased, there will be a tendency to "flash back."

It is sometimes thought that gas burners may be so designed as to give high efficiencies and at the same time not be susceptible to reasonably large changes in gas pressure and "gravity." This is not the case. The most efficient point of operation for any burner is just before the "flashing back" point. A burner operated at this point will be susceptible to very small changes in gas pressure and quality.

In order that a burner may be able to withstand considerable changes in pressure and "gravity" without "flashing back" it is necessary to operate it much below the highest efficiency.

This is somewhat analogous to the case of the incandescent electric lamp. The higher the voltage at which it is operated, the higher the efficiency of light production, but the greater the damage from the momentary application of even a small excess in voltage. For instance, if a tungsten filament electric lamp be designed to operate at .81 candles per watt (1.23 watts per candle) on 110 volts, and to have a useful life of 1,700 hours when operated at this point, an increase in voltage to 114 will cause the duty (see p. 75) to increase to .885 candles per watt (1.13 watts per candle), but the useful life will be reduced to 1,000 hours, or over one-third.

The most important features in good gas service are uniformity of pressure and quality. The candle-power standard gives no indication whatever of the value of a gas to the consumer except for use in open-flame burners, which are rapidly becoming obsolete. For most purposes high candle-power gas is much poorer than low candle-power gas, on account of the difficulty of entraining sufficient air to obtain the highest flame temperature.

Neither is the *heating* (or *calorific*) *value* of much impor-

tance, provided the price at which the gas is sold be commensurate. That is, if for a certain purpose 500,000 B. T. U.'s are required, and gas of 500 B. T. U.'s per cu. ft. is available at $1.00 per thousand cubic feet, or gas of 250 B. T. U.'s at $0.50 per thousand, it is immaterial to the user whether he purchases 1,000 cu. ft. of 500 B. T. U. gas for $1, or 2,000 cu. ft. of 250 B. T. U. gas for $1. The close regulation of gas pressure and uniformity of quality is of immensely greater importance than either calorific value or candle-power.

Having obtained a flame of the highest possible temperature, it is necessary next to consider the transferring of the heat from the flame to the material to be heated with the least possible loss.

Heat may be transferred from one body or place to another in three different ways:

First, by *conduction* by which heat is conducted through a body in much the way that electricity is conducted through a wire. Each particle on becoming heated transmits or conducts a portion of its heat to adjacent particles, and in this way the heat may be said to travel through the body. Different substances possess different capacities for conducting heat, or different *thermal conductivities*.

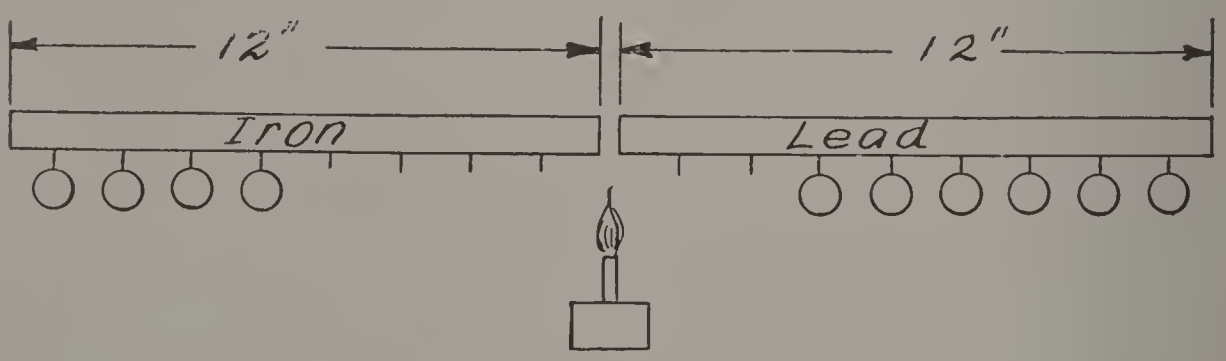


FIG. 8

Thus, if a bar of iron and a bar of lead of equal size (Fig. 8) be heated at one end of each, the heat will be more rapidly conducted through the iron, and this may be shown by attaching small balls by means of some fusible material which will melt at a low temperature.

The balls nearest the heated ends will drop first, and the successive dropping of the balls will indicate the rapidity with which the heat is being conducted by the metal. It will be thus seen that the iron is the better conductor.

Second, by *convection* or the actual moving of the heated body itself. An example of this is seen in the heating of water contained in a vessel heated at the bottom by a flame or other means (Fig. 9). The heat is transferred by *conduction*

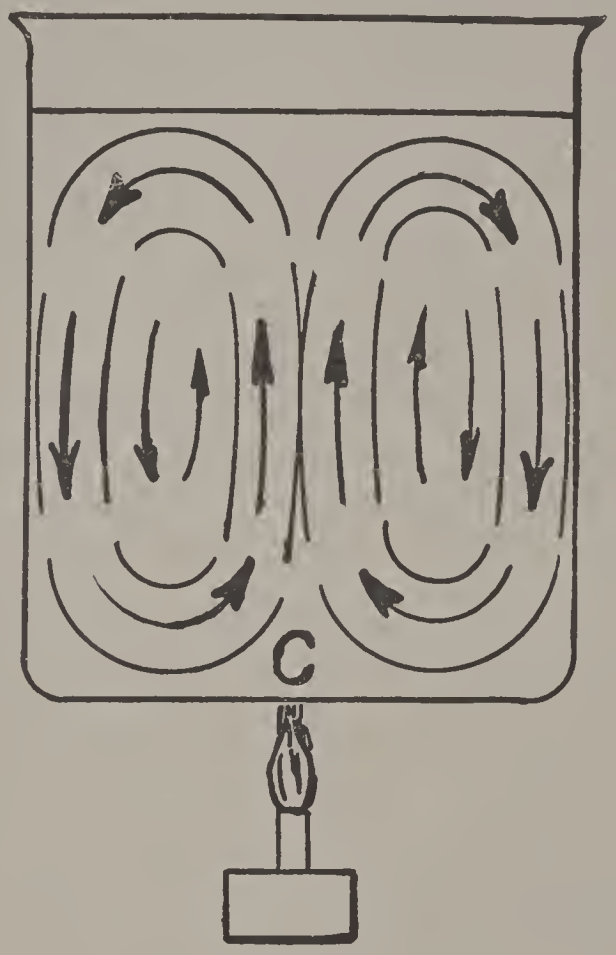


FIG. 9.

through the bottom of the vessel and to the water at "C." This water, becoming lighter by expansion, rises and cooler water from the top and sides of the vessel flows downward to take its place.

This water is heated in turn and the process repeated continuously, and the heat from the flame is transferred to all the contents of the vessel. Thus, the heat from the flame enters the vessel by *conduction*, and is distributed throughout the contents by *convection*, being carried by the circulating water currents.

Third, by *radiation*, in which energy is *radiated* (or sent out in rays) through a non-conducting medium (called the "æther") in the same manner as light. A somewhat similar action occurs when a stone is dropped into a pool of water. The motion imparted to the water is carried by the waves produced, throughout the surface of the pool, and energy is thus *radiated* to distant points. In fact, light rays are simply energy waves of certain lengths to which the "retina" of the eye is sensitive, and rays which are too long to affect the retina are often called *heat rays*. When these "energy waves" encounter objects which absorb them, heat is produced, and since bodies *produce* these energy waves by virtue of their *temperature,* this process furnishes a means of transmitting heat from one place to another, even though the intervening space be not a conductor of heat.

The heating of the earth's atmosphere by the sun involves all three methods of heat transferrence. First, the radiant energy sent out by the incandescent gases of the sun encounters the earth, and being absorbed and transformed into heat, the earth is warmed. This heat is transferred into the lower layers or *strata* of air by *conduction*, and these rising upward, make place for cooler air and set up a process of *convection*. The currents of air (or winds) so produced thus carry heat from one portion of the earth's surface to another.

In applying the heat of burning gases for any purpose we may make use of any or all of these methods of heat transferrence.

The most important thing to bear in mind is that the efficient use of gas for heating demands the reduction of heat losses to the lowest possible point.

Heat may be lost by conduction, convection or radiation. Losses in the first manner are comparatively easy to reduce since many substances, notably asbestos, firebrick, etc., conduct heat very poorly. Air is also a comparatively poor conductor, but since, if allowed to move about freely it carries away heat through convection, means must be taken to prevent this movement. Consequently, when air is used as a heat *insulator*

(or non-conductor) it must be held in small spaces or cells, such as are formed by a packing of cork, asbestos, mineral wool or the like. The substance used must, of course, be of a sort not affected by the temperature to which it will be subjected. The quantity of heat transferred by conduction is proportional to the time, to the conducting area, to the *difference* in temperature between the two points, and to the *thermal conductivity* (heat-carrying ability) of the material.

During a given time, with the same temperature differences between the ends of the bars, an iron bar $\frac{1}{2}''$ square ($\frac{1}{4}$ sq. in. in cross-section) will conduct away four times as much heat as one $\frac{1}{4}''$ square ($\frac{1}{16}$ sq. in. in cross-section).

In the same bar, twice as much heat will flow away under a difference of 4° in the temperatures of the ends as would flow under 2° difference. Practically the same law holds with reference to the loss of heat through a sheet of iron in contact with the air.

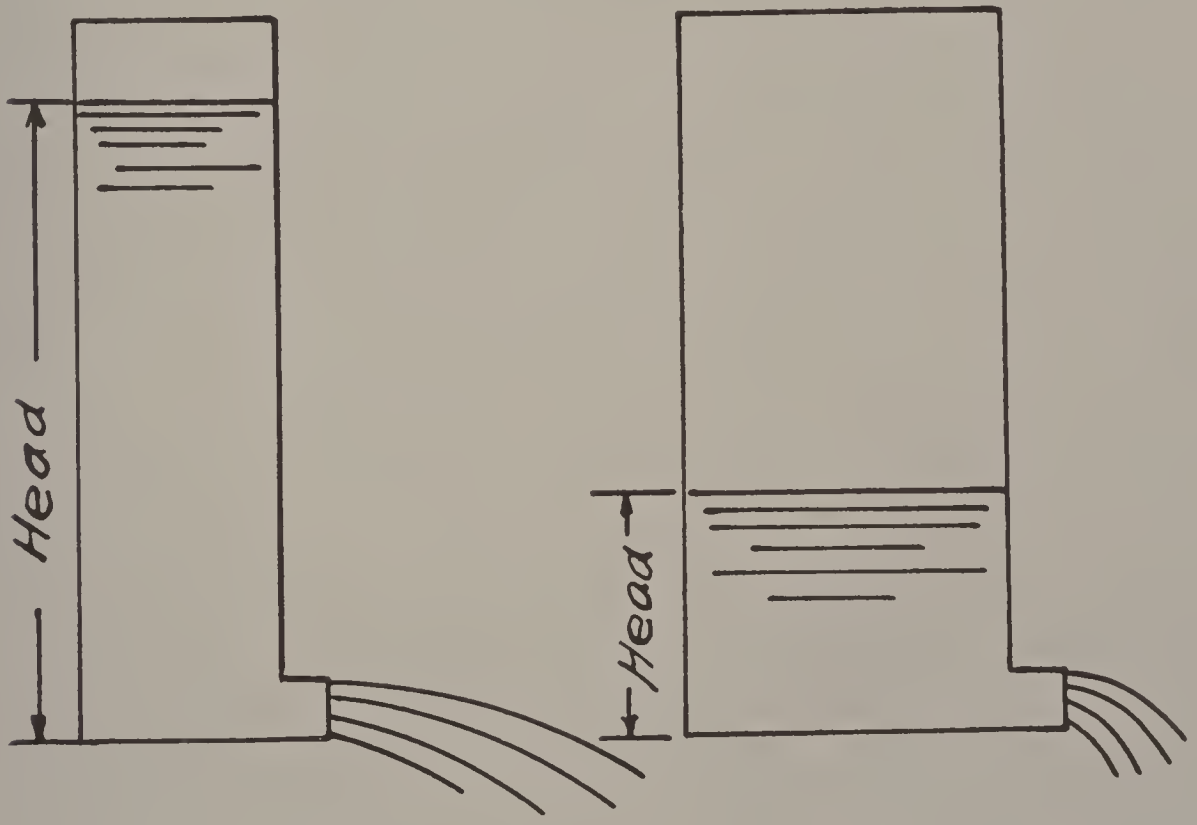


FIG. 10

Quite similar in principle to the conduction of heat is the transmission of water through pipes. At a given pressure or "head" more water will flow (in a given time) through a two-inch than through a one-inch pipe, and twice as much water will flow in 10 minutes as in 5 minutes. Through a pipe of given size more water will be discharged under high pressure than under low pressure, and more through a clean pipe than through a foul one, likewise more through a short pipe than through a long one.

The quantity of water delivered in a given time depends upon the velocity with which it issues from the pipe, and the area of the end of the hole from which it issues.

The velocity depends upon the "head" or pressure of the water and the friction which the water encounters in flowing through the pipe, which retards the velocity.

Fig. 10 illustrates the greater velocity (and hence quantity of water delivered from a given hole or orifice) due to greater pressure or head (corresponding to temperature difference).

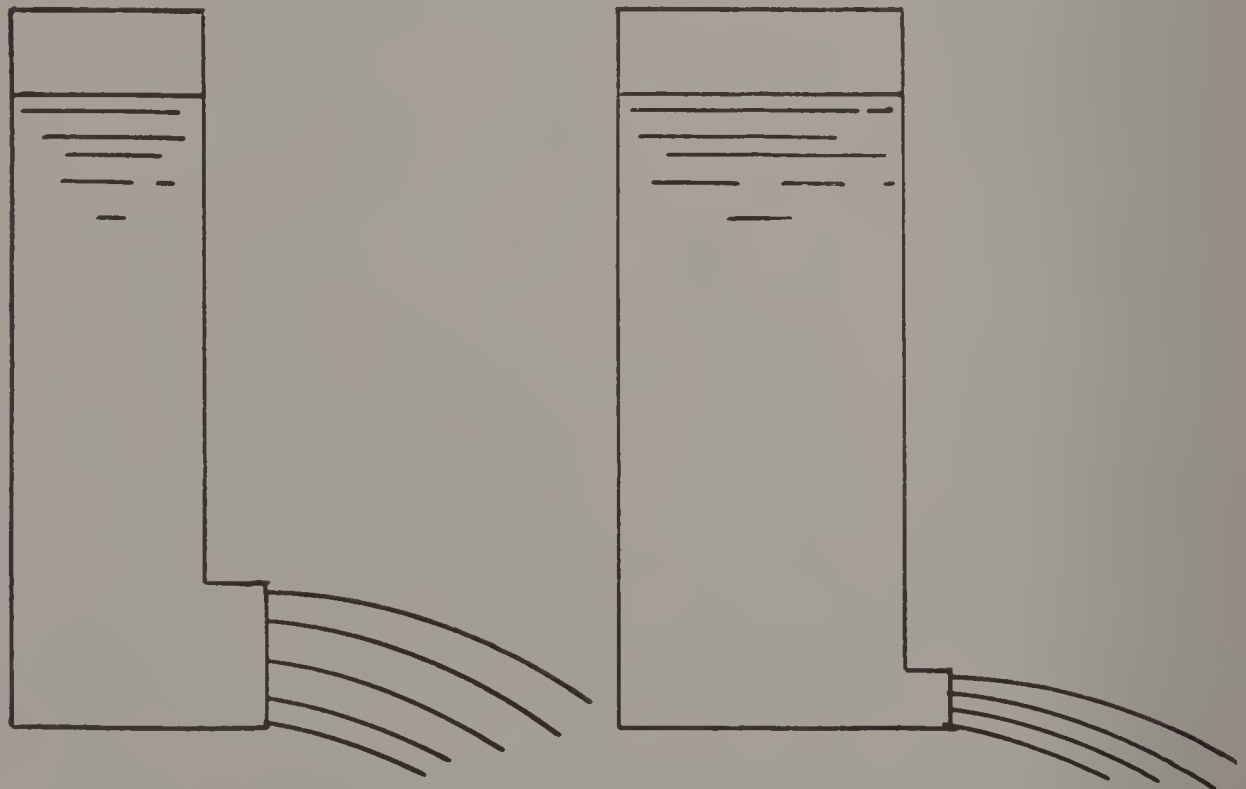


FIG. 11

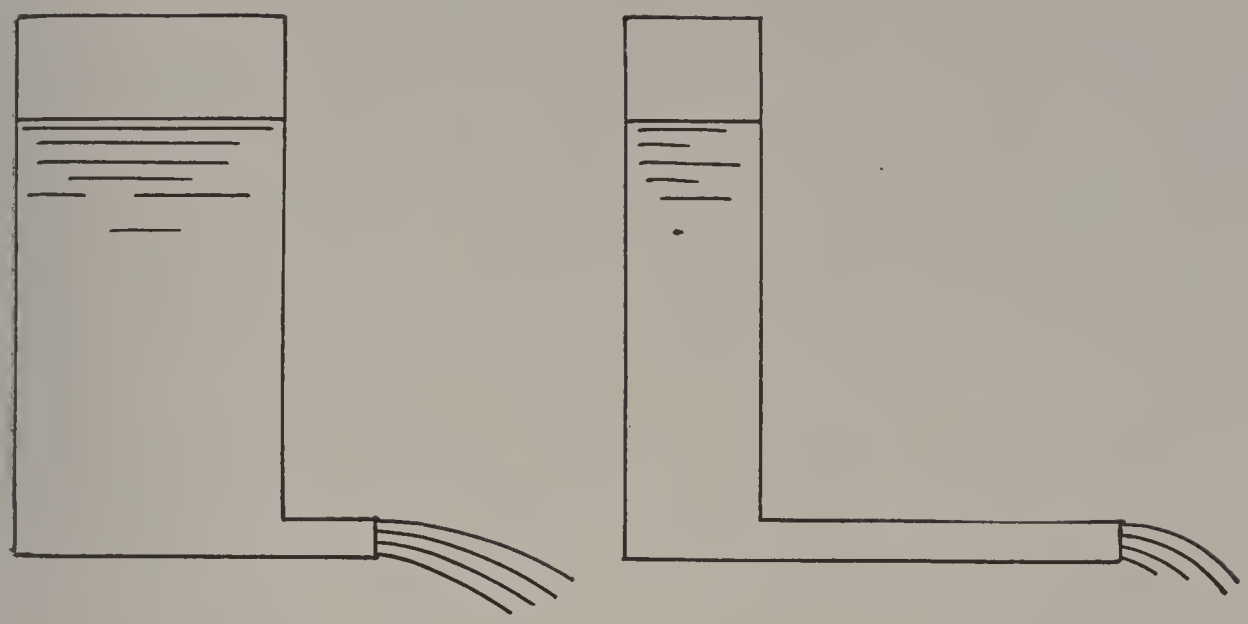


FIG. 12

Fig. 11 illustrates the greater quantity delivered at a given head or pressure (hence at the same velocity) through the larger orifice. Fig. 12 illustrates the reduced velocity (hence lesser quantity delivered) due to friction in a longer pipe.

Thus, to reduce heat losses it is necessary to reduce the *area* of heat conducting bodies and surfaces.

The escape of *radiant energy* may be practically prevented by surrounding the heated body by a reflecting surface, such as polished metal, which will reflect a large portion of the heat back into the heated body. Surrounding the heated body by insulating substances which absorb radiant energy and transform it into heat serve to retain a portion of the energy in the apparatus.

The well-known Thermos bottle (Fig. 13) for keeping liquid either cold or hot uses a vacuum (a perfect non-conductor) as insulation against the escape of heat by conduction or convection, and a mirrored surface to minimize radiation losses.

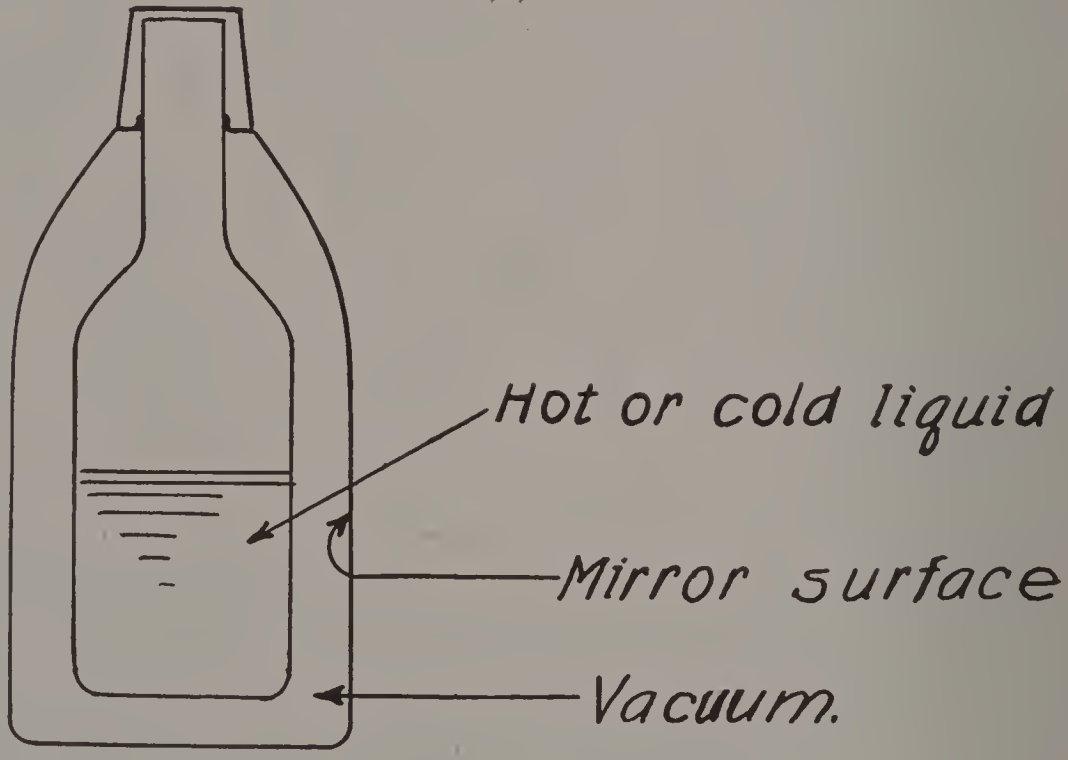
The amount of heat radiated from a body is proportional to the fourth power of the *absolute temperature* (491° plus Fahrenheit temperature), depending upon the material. An increase of 10° in the absolute temperature of a body will increase the quantity of heat radiated by 46 per cent. The quantity of heat

radiated will also depend upon the condition of the surface, being much less from smooth than from rough surfaces, and the temperatures of bodies receiving the radiation. This latter consideration is negligible except where the radiating body is at a temperature far below that of any gas flame.

The expedients that will be justified for minimizing heat losses in any particular device will depend upon commercial factors—the cost of applying or furnishing the means for reducing losses, the durability of the appliance, its weight, size, etc., and the cost of the combustible used to produce the heat, for obviously it would be foolish to spend more in saving heat than the heat itself is worth.

In very few processes is the mere cost of producing a certain amount of heat the main consideration. In domestic appliances, cleanliness, comfort and convenience are usually more important and more appreciated than mere economy.

In industrial appliances, on the other hand, the quality of the



Principle of Thermos Bottle

FIG. 13

product and the rapidity with which it may be turned out are likely to be of prime importance.

In certain special fields, hygienic considerations may be uppermost. All other things being equal, however, economy is the deciding factor, and it is always a point in favor of the appliance possessing it, and the salesman should always take pains to install the most economical appliance which will otherwise meet the customer's requirements.

Unfortunately, it is not easy to obtain comparative data on the relative economies of various appliances. This is due to the fact that most published reports upon the operation of appliances describe their performance with reference to one particular application under one condition, and no comparison is possible unless the conditions of test are identical, for it is only in this way that we determine whether or not the design of the appliance itself is responsible for the differences in performance. For instance, suppose we have two tests of steam engines, one consuming 12.5 pounds of dry steam per horsepower hour and one 12 pounds of steam superheated 150°. Unless we know the extent to which superheat affects the performance of this particular type of engine, we have no means of knowing whether the superheat or the design of the engine itself is to be credited with the improved economy.

Similarly, the statement that one lamp gives 20 candle-power for each cubic foot of gas burned while another gives 22 is of no use whatever; unless we know that both lamps were fitted with identical mantles and burned upon the same gas at the same pressure and upon the same day, for all these factors affect lamp performance. Even a difference in atmospheric humidity (the amount of moisture in the air) might account for the entire difference in performance.

Thus, before we may make the statement that one appliance is more efficient than another, we must first make sure that all conditions of test are identical in order that any differences in performance may properly be credited to the superiority of the appliance itself.

Furthermore, it is desirable to use some system of units for

expressing the energy contained in different fuels, etc., so that they may be compared with each other. It is not possible to make a direct comparison between a pound of coal and a cubic foot of gas, but by a third energy unit we may compare the *energy* in a pound of coal with that in a cubic foot of gas.

Such a unit is the British Thermal Unit before described. By means of "Conversion Tables" any unit of energy or work may be expressed in B. T. U.'s or *vice versa.*

This is possible because heat, being a mode of motion, is energy, and energy results in heat. The unit of work is the "foot-pound," the work required to raise one pound one foot, regardless of the time required in doing it. The unit of *rate of work* is the *Horse-power,* which is 33,000 foot pounds per minute—that is, 33,000 pounds raised one foot in one minute, or one pound 33,000 feet in one minute, or $\frac{33{,}000}{60} = 550$ pounds raised one foot in one second, etc. Thus, one horse-power expended continuously during one hour, or one H. P. hour = 33,000 x 60 = 1,980,000 ft. pounds. One B. T. U. = 778 ft. pounds. Thus, if a mass weighing one pound were dropped 778 feet into one pound of water at 62° F., the temperature of the water would be raised one degree. Kilo-watt hours, horse-power hours, etc., may always be expressed in B. T. U.'s or foot-pounds and *vice versa.*

A short table of conversion factors is here given.

1 ft. lb. = .001285 B. T. U. = .0003766 watt-hours = .0000003766 k.w. hours = .0000005051 H. P. hours.

1 B. T. U. = 778.1 ft. lbs. = .293 watt-hours = .000393 H. P. hours = .000293 k.w. hours.

1 Kilo-watt hr. = 2655000 ft. lbs. = 1.34 H. P. hr. = 3413 B. T. U.'s.

1 Horse-power hr. = 1980000 ft. lbs. = 745.6 watt-hours = .7456 k.w. hours = 2544 B. T. U.'s.

The *efficiency* of an appliance or machine is the ratio between the energy utilized by the appliance and that furnished to it.

Efficiency as used in this sense must not be confused with the ordinary conversational use of the word in which it signifies adaptability to a desired end. It deals with energy units only. Efficiency may be measured or determined in two ways, the work done by the machine and the energy put into it may be measured, and the former divided by the latter, or, the losses may be measured and subtracted from the energy put in, the result being divided by the energy put in. An example of the first method is the determination of the efficiency of a range top burner by burning a given quantity of gas in the burner (the B. T. U.'s of the gas being known) and measuring the increase in temperature of a known weight of water in a vessel above the burner. Suppose the vessel to contain 8 pounds of water at 40° F. before the test. After burning one cu. ft. of gas under it the temperature rises to 70° F. The rise in temperature is 30°. If the gas contains 600 B. T. U.'s (as determined by previous experiment) this amount of heat would be sufficient to raise one pound of water 600° or 8 pounds $\frac{600}{8} = 75°$ if all the heat were used. Since the actual rise is

but $30° \frac{30}{75} = 40$ per cent. of the heat in the gas has entered the water and the efficiency of the appliance is 40 per cent.

Sometimes it is more convenient to ascertain the *losses* than to measure the *useful work*. For instance, it is often inconvenient to place an artificial load on electrical apparatus of high capacity in order to ascertain the performance under load. In testing large transformers it is often found convenient to supply only enough energy to supply the *losses* and to calculate the efficiency from these measurements. If the losses corresponding to full load operation in a 1,000 k.w. transformer are found to be 20 k.w., then the efficiency at full load is $\frac{1{,}000 - 20}{1{,}000} =$ 98 per cent.

The combined or over-all efficiency of a combination of apparatus is the product of the efficiencies of the different parts. For instance, suppose an installation to be composed of a steam boiler having an efficiency of 70 per cent., a steam engine of 20 per cent. and an engine-driven pump of 95 per cent. For every 100 heat units in the coal 70 per cent. or 70 heat units will be utilized in the boiler. Of these 70 units 20 per cent. or ($70 \times .20 =$) 14 will be utilized in the engine, and 95 per cent. of the 14 or ($14 \times .95 =$) 13.3 will be useful for pumping water. Thus, the over-all efficiency is $.70 \times .20 \times .95 = .133 = 13.3$ per cent.

The word efficiency is sometimes loosely used to signify the amount of energy in one form obtained from a given amount in another form, such as the number of candle-power given by each watt of electricity or cu. ft. of gas consumed per hour. Thus, an incandescent electric lamp consuming 64 watts per hour and giving 16 horizontal candle-power is said to have an efficiency of $\left(\frac{16}{64} =\right)$ .25 candles per watt, or $\left(\frac{64}{16} =\right)$ 4 watts per candle. To express this and similar quantities the term *duty* is preferable, and will be used throughout this course. *Duty* should always be expressed in quantity of product for each unit of energy consumed—that is, the *duty* of an electric lamp should be given in *candles per watt* rather than watts per candle. The latter has been most generally used because the figures for the incandescent lamp happen to come in whole numbers $\left(\frac{64}{16} = 4\right)$ while the former comes as a fraction $\left(\frac{16}{64} = .25 = \frac{1}{4}\right)$.

PART II

UNITS OF LIGHT AND ILLUMINATION AND LAWS OF LIGHT TRANSMISSION

In passing from the luminous source to the eye, light passes through various processes and undergoes various changes all of which absorb a certain amount of light and thus affect the quantity delivered to the eye as available for producing vision. It is therefore necessary to formulate units by which light may be measured so that the efficiency of these processes may be determined. The utilization of light may be compared to the utilization of steam or electricity, and the various processes may be divided into the following group:

I *Production.*—The light source corresponds to the steam boiler or electric generator, where energy is turned into the form in which it is to be transmitted.

II *Transmission.*—The æther* through which light waves are propagated) and the various reflecting surfaces, including the lamp equipment and the illuminated objects, correspond to the steam piping or electric transmission and distribution system, through which the energy is carried to the apparatus in which it is to be utilized.

III *Utilization.*—The eye corresponds to the steam engine, electric motor, lamp or heating apparatus, in which the transmitted energy is converted into the form in which it is desired to use it—mechanical power in the steam engine, mechanical power, light, or heat in the case of electricity, and the sensation of sight in the case of light.

It is therefore necessary, first of all, to devise some means

* To explain certain known facts concerning the nature and behavior of light waves, it is necessary to assume the existence of a substance which pervades all matter and space, even the densest metals and the most perfect vacuum. This substance possesses some of the characteristics of solids and is called the "æther." (See any good encyclopedia or text-book on physics.)

of measuring the quantity of light produced at the source. Since the results produced by light are, broadly speaking, apparent to the eye only, and as a physiological sensation which cannot be translated into terms of energy, it is necessary to fix upon some arbitrary unit such as the quantity of light produced by a lamp of definite form designated as the standard when operating under certain definite conditions.

Obviously, the standard lamp must be of such a sort that the quantity of light emitted is not affected except by controllable conditions.

Thus, the electric arc is useless for this purpose because even when furnished with electrical energy at fixed voltage and of fixed current value, the quantity of light varies enormously, due to the uncontrollable eccentricities of the arc. The most widely used standard is the Vernon-Harcourt Pentane lamp invented by the eminent English engineer of that name. When manufactured according to certain specifications concerning the sizes and arrangement of parts this lamp is used as the standard for measuring light. It is adjusted to burn a certain definite quantity of pentane per hour, and the barometric pressure and amount of moisture (humidity) and of carbon dioxide (CO_2) in the air are determined at the same time.

Since by previous experiments the effects of different barometric pressures and amounts of moisture and of CO_2 in the air are known, the results may be corrected to certain standard conditions.

From the light given by this standard lamp the unit of light measurement must be derived. The total amount of light given out would seem to be the most rational value for this unit, but since the eye which is the only instrument sensitive to light, can only view the light source from one point, it is impossible to make a direct measurement or estimate of the total light emitted in this way. As the quantity of light given out is different in different directions, it is necessary to select one particular direction in which to measure the light. The horizontal has been selected for this purpose because it is

easily determined and lends itself well to the construction and operation of photometrical apparatus.

Having determined the kind of source and the direction which shall furnish the unit quantity of light, we must next determine the size of the beam to be used for this purpose. Just as a large pipe will under a certain pressure deliver more gas during a specified time than a small one, so a large beam of light from a certain source will contain more light than a small one.

As a unit for measuring the size of a beam of light the *solid angle* is used. This is perhaps more easily illustrated than defined.

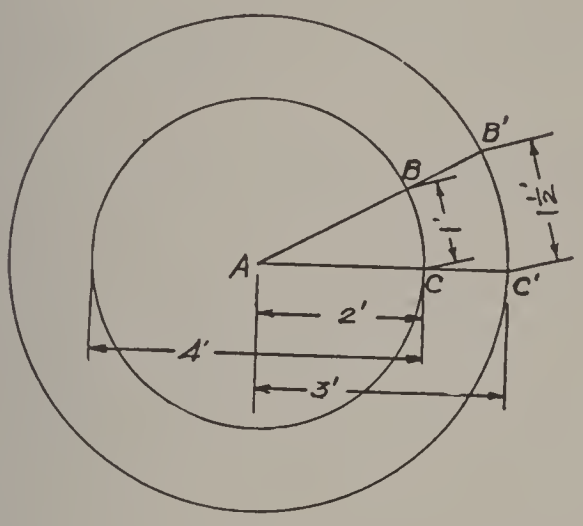


FIG. 1

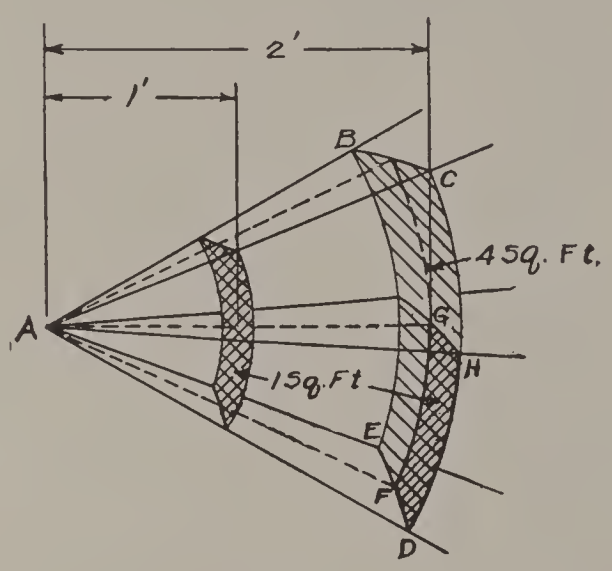


FIG. 2

The term *angle* signifies *degree* of *divergence*. For instance, if two straight lines meet at a point (Fig. 1) they form an *angle,* and this angle is a measure of the divergence between the lines. The angle is measured by the ratio between the *arc* (BC or B′C′) of any circle drawn about the meeting point of the lines as a centre, and the *radius* of the same circle AC or AC′. Thus, $\frac{BC}{AC}$ or $\frac{B'C'}{AC'}$ is the angle expressed in *radians*. The term radian is used in scientific works because of its greater simplicity for certain calculations. In

practice angles are measured in *degrees,* one degree being the angle measured by $\frac{1}{360}$th of the *circumference* of the *circle.* For scientific purposes, however, the degree is unwieldy and introduces complicated calculations.

Thus, if in Fig. 1 a circle of 2′ radius (4′ diameter) be struck about A as a centre and the diverging lines AB and AC cut off an arc BC of 1′ in length on this circle, the angle is $\frac{1}{2} = .5$ radians.

Similarly, if a circle of 3′ radius be struck the arc B′C′ will be 1½′ in length and the angle $\frac{1\frac{1}{2}}{3} = .5$ radians. No matter what size of circle be used, the expression for the angle between the two lines remains the same.

The term "solid angle" is quite similar, except that instead of lines, we are dealing with *planes,* and instead of circles—spheres. Thus, if in Fig. 2 we have four lines AB, AC, AD, AE diverging from the point A, they will form the corners of a pyramid, the sides of which will cut off an area BCDE on the surface of any sphere described around the point A as a centre.

Just as a plane angle is measured by the ratio of the *arc* to the *radius* of a circle, so the solid angle is measured by the ratio of the area cut off of any sphere to the square of the radius of the same, and this quantity will be constant for any given solid angle regardless of the diameter of the sphere. The unit for solid angle measurement is the *steradian.* If in Fig. 2 the radius of the sphere is 2 ft. and the area BCDE contain four square feet the solid angle is $\frac{4}{2^2} = \frac{4}{2x2} = 1$ steradian.

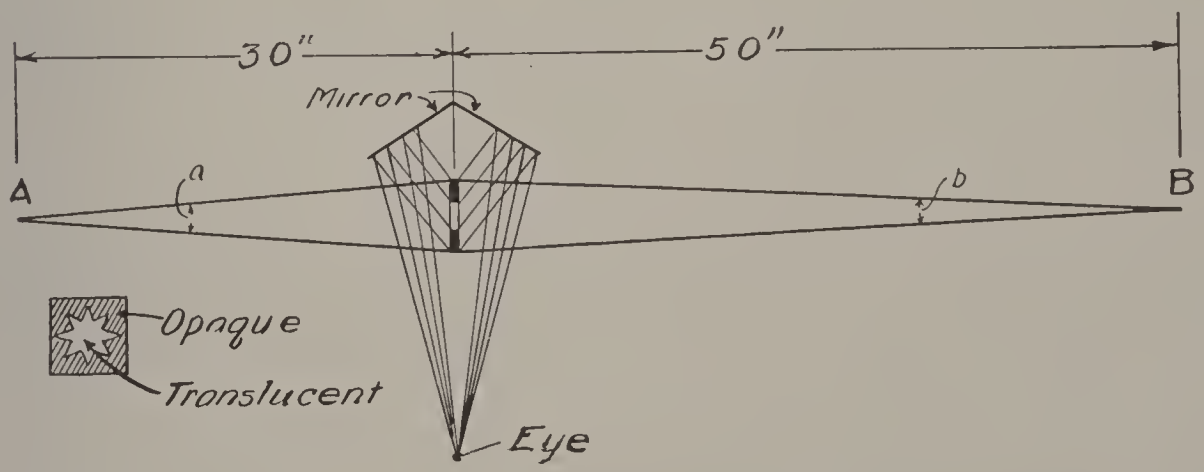
No matter what form the area BCDE may take, whether it be cut off by a cone, a pyramid or an irregular shape bounded by lines diverging from "A," the solid angle at "A" is measured in the same way.

Applying this to the particular problem of a beam of light from a point source, it is easily seen that if the point A is emitting light equally in all directions inside the pyramid ABCDE, the smaller pyramid AFGHD will contain less than the larger pyramid, and in proportion to the areas FGHD and BCDE. That is, if FGHD is one-fourth of the area of BCDE, then the quantity of light in the smaller beam or pyramid will be one-fourth of that in the larger one.

Having determined upon a standard light source, and a standard direction in which to measure it, it only remains to select a size of beam which we will fix upon as containing the quantity of light, which we shall use as a unit. We may select for this purpose any solid angle we like, but it will be best to consider how the ease of mathematical calculations, etc., will be affected.

In order to make the new unit conform in magnitude to the ones previously used, let us select a solid angle of 1 steradian*

* In making actual measurements, however, it will be necessary to use a much smaller angle (say 1-100 steradian) since the distribution of light from the lamp varies considerably within a solid angle of 1 steradian. The measurement of quantity of light is based upon the fact that equal quantities of light falling upon surfaces of equal area and identical material



Principle of Bunsen Photometer.

will produce equal degrees of brightness—that is, upon the same surface, equal quantities of light per square inch will produce equal degrees of brightness. The apparatus used for measurements of this character is called a photometer and exists in a variety of forms. The Bunsen Photo-

as representing the size of the standard beam of light, from the standard lamp in a horizontal direction. Let us take one-tenth the quantity of light in this beam in the unit for measuring and comparing quantities of light, since the present standard lamp is 10 times the power of the earlier standard. We may call it what we like, but must select a word not heretofore in use.

The word *lumen* will serve to indicate the luminous nature of the commodity which we will measure in this way, and is distinctive and easily remembered and pronounced. Therefore we will call the new unit the lumen.

This unit may be used to describe any quantity relating to light. For instance, if we wish to describe the brightness of a

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meter, the principle of which is illustrated above, is perhaps the form most widely used. It consists of a screen, the central portion of which is translucent and the outer portion opaque. The screen was originally made by applying grease to the centre of a paper disc. Mirrors are provided enabling both sides of the screen to be seen at the same time. When equal quantities of light fall upon each side of the screen, the same *degree of contrast* between the centre and outer portion is shown upon each side. The apparatus is then said to be "in balance." (Some authorities state that when "in balance" the central spot "disappears," the whole field being of uniform brightness. That this is not and could not possibly be the case will be quite evident to any one who will take the trouble to think about the matter for a few minutes).

When the screen is "in balance" the quantity of light per steradian from the lamp under test is calculated as follows: Suppose the lamp at A to emit light at the horizontal at one lumen per steradian. If the screen be 2″ square and 30″ distant from A, the solid angle "a" is $\left(\frac{2 \times 2}{30 \times 30}\right) = .0044$ steradians and the quantity of light falling upon the side of the screen facing A is .0044 lumens. Since the same amount of light is also falling upon the side of the screen facing B, the quantity of light in the solid angle "b" is likewise .0044 lumens. The solid angle "b" is $\left(\frac{2 \times 2}{50 \times 50}\right) = .0016$ steradians. Since the light from B in .0016 steradians is .0044 lumens, the quantity light in one steradian will be $\left(\frac{.0044}{.0016}\right) = 2.8$ lumens (nearly).

It will be seen that in these calculations the area of the screen and the illumination is the same in both cases. These quantities therefore disappear and the final calculations may be made by using only the squares of the respective distances from the lamps to the screen. Thus $\left(\frac{50 \times 50}{30 \times 30}\right) = \left(\frac{2500}{900}\right) = 2.8$ (nearly).

flame, a mantle or an illuminated wall or ceiling, we may do so in terms of lumens per steradian per square inch or per square foot, meaning the quantity of light emitted per unit area in a given direction. Obviously, 1 lumen emitted by an area of one square inch will produce a brighter surface than 1 lumen emitted by 10 square feet. On the other hand, if we wish to describe the degree to which illumination is concentrated upon a lighted area, we may again express it in lumens per square foot, meaning the quantity of light *received* by each square foot of the surface. The difference between the amount of light received by a surface (not self-luminous) and that emitted by it is the amount absorbed by the surface.

Excepting color, the only characteristics of illuminated surfaces in which we are interested is the distribution of surface brightness, and it is plainly more sensible to express this by the use of a unit which also designates the quantity of light available for illumination, than to use units (candle-power, foot-candles, etc.) which must be transformed into more logical units before they can be used to convey any intelligible idea concerning illumination. In order to avoid confusion, however, the value of the lumen has been so selected that one lumen per square foot is equal to one foot-candle.*

If artificial light sources gave out equal quantities of light in all directions, a simple statement of the quantity in any one direction would convey sufficient information concerning the characteristics of a lamp. This is not the case, however, so it is necessary to devise some means of showing the quantities given out in various directions in a simple and convenient form. Such information may be conveyed in the form of tables in which the quantity of light in a beam of standard size in each direction is shown. If we designate the directions by angles we must first select a certain direction to be designated by zero as a point of reference. The direction of a point immediately below the lamp is universally used as the zero or

* The use of the term candle-power is perfectly logical if it is regarded only as a short equivalent for 1 lumen per steradian and *not* as a fundamental or basic unit of light measurement.

reference point and the horizontal is designated by 90°. Suppose that in a beam of 1/100 steradian (a beam so small that we may expect the distribution of light to be uniform within it) directly downward from the lamp shown in Fig. 3 the quantity of light is found to be .88 lumens; at the horizontal,

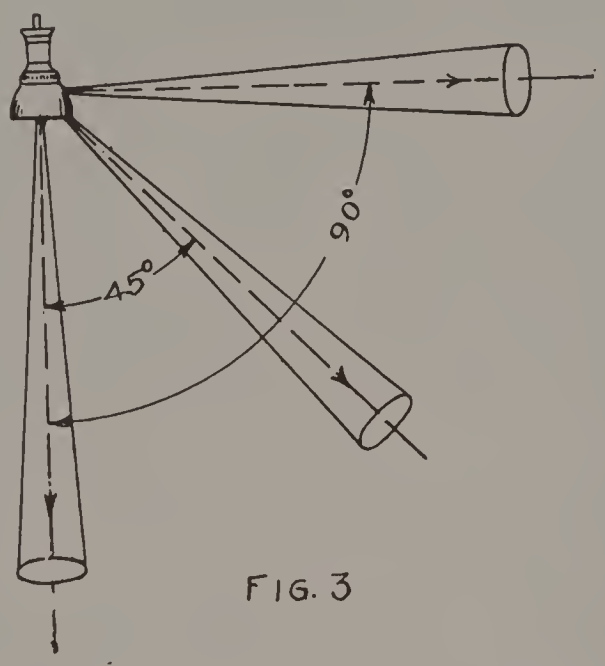

FIG. 3

.34 lumens; midway between (at 45°), 136 lumens; directly upward (180°), .15 lumens, and at 135°, 35 lumens.

We may tabulate this information as below:

Angle	Quantity of Light in $\frac{1}{100}$ Steradian	Quantity of Light per Steradian
0°	.88 lumens	88 lumens
45°	1.36 "	136 "
90°	.34 "	34 "
135°	.35 "	35 "
180°	.15 "	15 "

For most purposes, however, it is necessary to know the quantities of light at many intermediate angles.

Such a table would occupy much space and would not convey a very graphic idea of the manner in which the light is distributed.

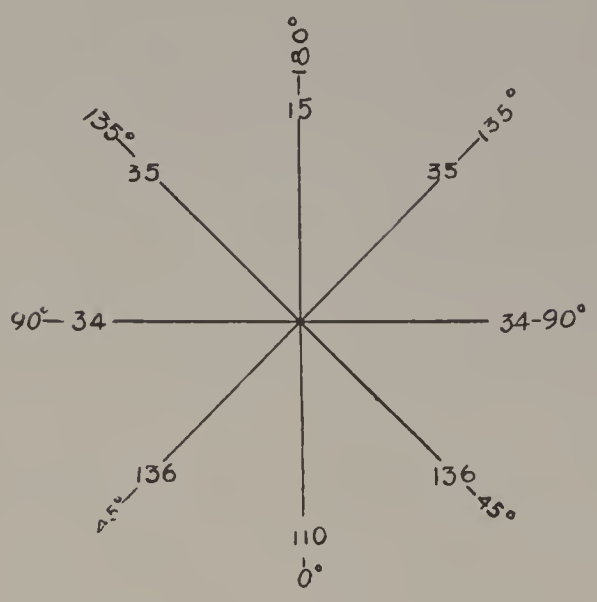

FIG 4

We therefore substitute for the column of angles a chart composed of lines actually drawn at the angles required, and place upon each line a figure representing the quantity of light in that direction (Fig. 4).

But this arrangement, though economizing space, does not show at a glance distribution of light. It is still necessary to pick out the different figures and compare them, so we adopt the expedient of placing each figure at a distance from the centre proportional to the amount designated (Fig. 5). This, however, is a rather awkward form, as in order to show the values at all intermediate angles, the number of lines and figures becomes confusingly large. We therefore drop the use of figures entirely, placing dots at the distances from the centre

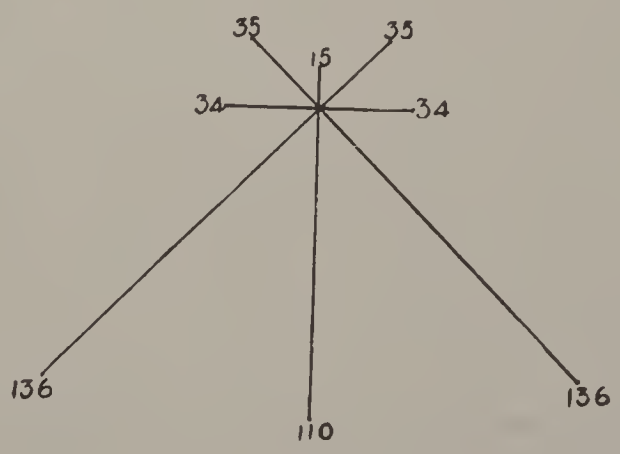

FIG. 5

proportional to the quantities of light and connect all these dots by a smooth curve. We place a scale (Fig. 6) by which these values may be determined upon the vertical line and provide circular lines by means of which this scale may be transferred upon any line representing an angle, and the quantity of light read at a glance, the form of the curve showing the characteristics of light distribution for this particular lamp and reflector.

It will be seen that as we have determined the quantities of light at different angles in one vertical plane only (Fig. 7), we have no means as yet of finding the total amount of light given by the lamp. This will receive attention later.

Having determined the quantities of light in beams of standard size at different angles, and arranged the results in a convenient form for reference, we are next interested in ascertaining the degree to which this light will be concentrated over

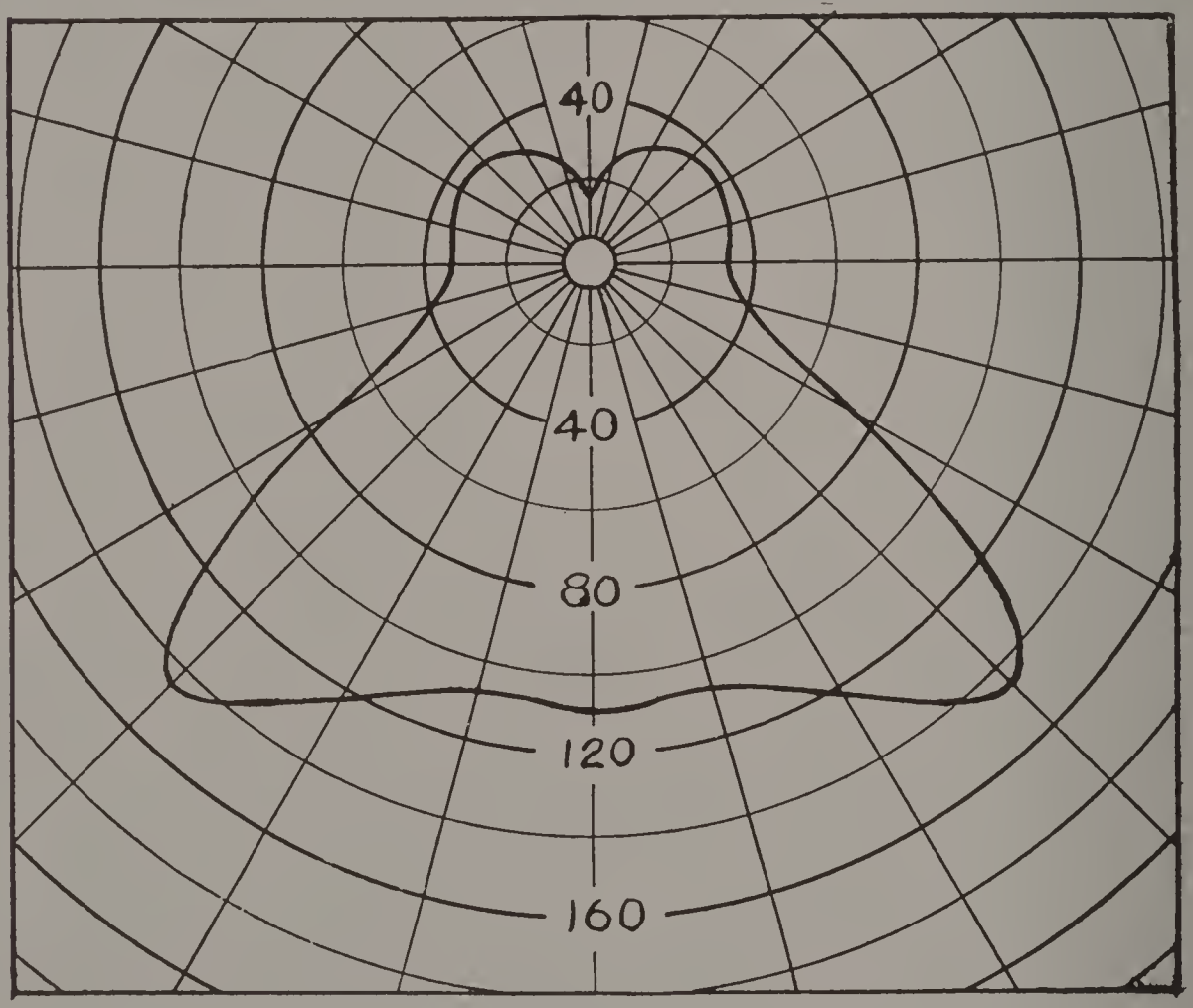

FIG. 6.

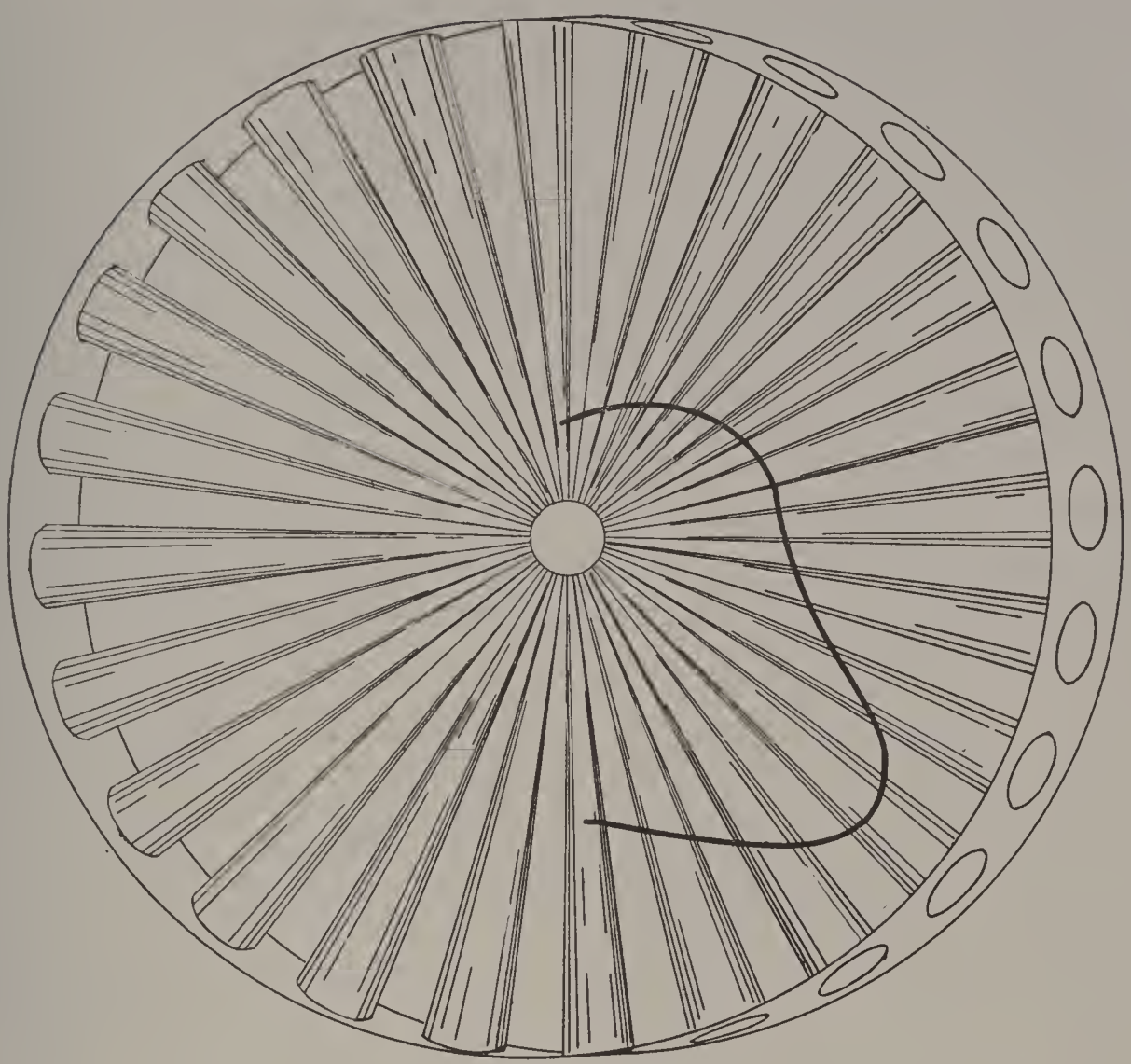

FIG. 7

surfaces in different positions and at different distances. If our light source is so small that it practically may be regarded as a point emitting light in all directions, the area covered by each beam will be greater as the distance from the lamp increases (Fig. 8) and also as the angle of inclination between the beam and the illuminated surface increases (Fig. 9). If the surfaces are perpendicular to the beam, it is quite easy to show that at 2 feet from the lamp a beam of a given size will cover *four* times as great an area as at 1 foot (Fig. 8), and at 3 feet, *nine* times as great. In other words, the area covered is proportional to the square of the distance, and as the greater the area covered by a given quantity of light, the more

thinly it will be spread (so to speak) and the less brightly the surface will be illuminated. The illumination is said to vary inversely as the square of the distance, and by some writers this is called the "Law of Inverse Squares." It is nothing of the sort. It is merely a statement of mathematical relations having nothing whatever to do with the laws of light.

It may properly be called the *Rule* of Inverse Squares, bearing in mind that it refers only to single light sources, which are practically points emitting light in diverging rays.

The extent to which the areas covered by a beam of light are increased by inclining the lighted surface to the beam is not susceptible of such simple statement, and for practical purposes it is more convenient to make use of the tables of *con-*

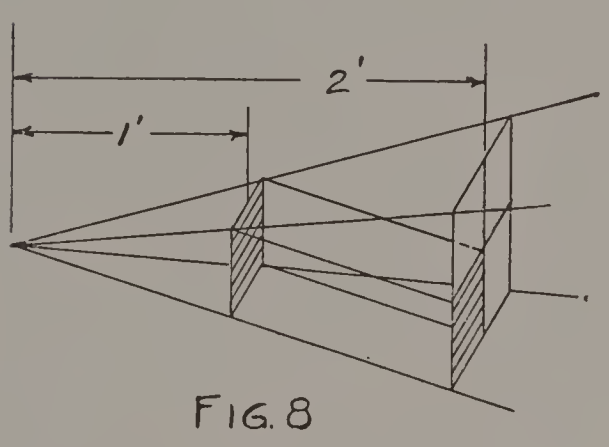

FIG. 8

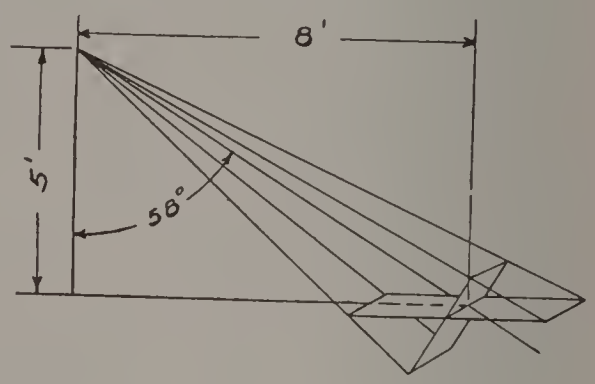

FIG. 9

stants or *factors* supplied for such calculations in the various hand and text-books available.

These tables are usually gotten out in the form of factors by which to multiply the light quantities at angles designated in the tables as corresponding to certain distances below and out from the lamp, and give results in terms of lumens per square foot.

Thus (see Table 1) if we wish to determine the illumination on a horizontal plane at a point 8 feet out from directly beneath the lamp (the distribution curve of which is shown in Fig. 6) and in a plane 5 feet below the lamp, we find from the table that the factor is .00595 and the angle 58°. (See Table 1.)

The figure .00595 is the *reciprocal* * of the area covered by the beam at this distance and angle of inclination.

This is used because multiplication is easier than division. The area covered is approximately 168.067 sq. ft. Since multiplying by .00595 produces the same result as dividing by 168.067 and the operation is more quickly and easily performed, these factors are given in the form of reciprocals by which the quantity of light at the angle specified must be multiplied. Thus, we find the illumination on a horizontal plane at the point designated to be $360 \times .00595 = .342$ lumens per sq. ft. To find the *normal* illumination, or that at the same place upon a plane squarely facing the light source, use the proper factor, .0112 (Table 1). $360 \times .0112 = 4.032$ lumens per sq. ft.—the normal illumination. Notice that this calculation holds only for a single point, or rather a small area at the designated location, and not over the entire surface covered by the beam of standard size (1 steradian. This size was adopted purely for convenience in order to make the new units conform to the old in magnitude. The actual measurements of light quantity are made upon a much smaller beam (1/100 steradian or less). This in nowise affects the accuracy of the results, merely the magnitude of the mathematical quantities under consideration, which are so selected as to eliminate discrepancies in final results.

As stated above, the new units have been so selected that they may be used in connection with old candle-power curves and foot-candle data. Thus:

1 lumen per steradian = 1 candle-power.
1 lumen per sq. ft. = 1 foot-candle.

In this way no confusion will arise in using the new and more logical units in place of the old.

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*The reciprocal of a number is 1 divided by the number. Multiplying by the reciprocal of a number is the same as dividing by the number. Thus, the reciprocal of 4 is 1 = .25. Multiplying by .25 is the same as dividing by 4.

TABLE I.

TABLE OF ANGLES, HORIZONTAL AND NORMAL FOOT-CANDLE CONSTANTS FOR DIFFERENT HEIGHTS AND DISTANCES.

	0′	1′	2′	3′	4′	5′	6′	7′	8′	9′	10′	12′	14′	16′	18′	20′	22′	24′
	0°	26°35′	45° 0′	56°20′	63°25′	68°10′	71°35′	74° 5′	76° 0′	77°30′	78°40′	80°30′	81°50′	82°55′	83°40′	84°20′	84°50′	85°15′
2′	.25	.179	.0884	.0426	.0224	.0129	.00788	.00516	.00354	.00253	.00191	.00112	.000717	.000469	.000341	.000242	.000183	.000142
	.25	.200	.125	.0768	.0500	.0347	.0249	.0188	.0146	.0117	.00972	.00678	.00505	.00380	.00309	.00245	.00203	.00171
	0°	18°25′	33°40′	45° 0′	53°10′	59° 0′	63°25′	66°50′	69°25′	71°35′	73°20′	76° 0′	77°55′	79°55′	80°30′	81°30′	82°15′	82°50′
3′	.111	.0949	.0641	.0393	.0241	.0152	.00996	.00677	.00483	.00350	.00262	.00157	.00102	.000688	.000500	.000359	.000272	.000215
	.111	.100	.0770	.0555	.0402	.0295	.0222	.0172	.0137	.0111	.00913	.00649	.00487	.00374	.00303	.00243	.00202	.00172
	0°	14° 0′	26°35′	36°50′	45° 0′	51°20′	56°20′	60°15′	63°25′	66° 0′	68°10′	71°35′	74° 5′	76° 0′	77°30′	78°40′	79°40′	80°30′
4′	.0625	.0571	.0447	.0320	.0221	.0152	.0106	.00764	.00560	.00421	.00321	.00197	.00129	.000885	.000631	.000474	.000361	.000281
	.0625	.0588	.0500	.0399	.0312	.0239	.0191	.0154	.0125	.0103	.00863	.00624	.00470	.00366	.00291	.00241	.00201	.00170
	0°	11°20′	21°50′	31° 0′	38°40′	45° 0′	50°10′	54°30′	58° 0′	60°55′	63°25′	67°25′	70°20′	72°40′	74°30′	76° 0′	77°10′	78°15′
5′	.0400	.0377	.0320	.0252	.0190	.0141	.0105	.00783	.00595	.00459	.00358	.00226	.00152	.00106	.000763	.000566	.000438	.000338
	.0400	.0384	.0344	.0294	.0243	.0199	.0164	,0135	.0112	,0944	.00800	.00588	.00452	.00356	.00285	.00234	.00197	.00166
	0°	9°30′	18°25′	26°35′	33°40′	39°50′	45° 0′	49°25′	53°10′	56°20′	59° 0′	63°25′	66°50′	69°25′	71°35′	73°20′	74°45′	76° 0′
6′	.0278	.0266	.0237	.0199	.0160	.0126	.00982	.00765	.00598	.00473	.00379	.00249	.00169	.00121	.000876	.000655	.000505	.000393
	.0278	.0269	.0250	.0222	.0192	.0164	.0139	.0118	.00997	.00853	.00736	.00556	.00429	.00344	.00277	.00228	.00192	.00162
	0°	8°10′	15°55′	23°10′	29°45′	35°30′	40°35′	45° 0′	48°50′	52°10′	55° 0′	59°45′	63°25′	66°20′	68°45′	70°45′	72°20′	73°45′
7′	.0204	.0198	.0181	.0159	.0134	.0110	.00894	.00722	.00582	.00471	.00385	.00261	.00183	.00132	.000972	.000731	.000570	.000447
	.0204	.0200	.0188	.0173	.0154	.0135	.0118	.0102	.00884	.00767	.00671	.00518	.00409	.00329	.00268	.00222	.00188	.00159
	°	7°10′	14° 0′	20°35′	26°35′	32° 0′	36°50′	41°10′	45° 0′	48°25′	51°20′	56°20′	60°15′	63°25′	66° 0′	68°10′	70° 0′	71°35′
8′	.0156	.0153	.0143	.0128	.0112	.00953	.00801	.00667	.00552	.00459	.00381	.00266	.00191	.00140	.00105	.000805	.000625	.000493
	.0156	.0154	.0147	.0136	.0125	.0112	.0100	.00886	.00781	.00691	.00610	.00480	.00385	.00313	.00258	.00216	.00183	.00156
	0°	6°20′	12°30′	18°25′	24° 0′	29° 5′	33°40′	37°50′	41°40′	45° 0′	48° 0′	53°10′	57°15′	60°40′	63°25′	65°45′	67°45′	69°25′
9′	.0123	.0121	.0115	.0105	.00941	.00824	.00712	.00608	.00515	.00436	.00370	.00266	.00195	.00145	.00111	.000855	.000670	.000536
	.0123	.0122	.0118	.0110	.0103	.00943	.00855	.00770	.00689	.00616	.00556	.00444	.00360	.00296	.00248	.00208	.00177	.00152

	0′	1′	2′	3′	4′	5′	6′	7′	8′	9′	10′	12′	14′	16′	18′	20′	22′	24′
	0°	5°45′	11°20′	16°40′	21°50′	26°35′	31° 0′	35° 0′	38°40′	42° 0′	45° 0′	50°10′	54°30′	58° 0′	60°55′	63°25′	65°35′	67°25′
10′	.0100	.00980	.00943	.00879	.00800	.00715	.00630	.00550	.00476	.00410	.00354	.00263	.00196	.00149	.00115	.000897	.000706	.000566
	.0100	.00984	.00961	.00917	.00862	.00799	.00735	.00671	.00610	.00552	.00500	.00410	.00337	.00281	.00236	.00200	.00171	.00147
	0°	5°10′	10°20′	15°15′	20° 0′	24°25′	28°35′	32°30′	36° 0′	39°15′	42°15′	47°30′	51°50′	55°30′	58°35′	61°10′	63°25′	65°25′
11′	.0082	.00816	.00787	.00742	.00686	.00624	.00560	.00496	.00438	.00384	.00335	.00255	.00195	.00150	.00117	.000927	.000741	.000595
	.0082	.00819	.00800	.00769	.00730	.00685	.00637	.00588	.00541	.00496	.00452	.00377	.00315	.00265	.00224	.00192	.00165	.00143
	0°	4°45′	9°30′	14° 0′	18°25′	22°35′	26°35′	30°15′	33°40′	36°50′	39°50′	45° 0′	49°25′	53°10′	56°20′	59° 0′	61°25′	63°25′
12′	.00694	.00687	.00666	.00634	.00593	.00547	.00497	.00448	.00400	.00356	.00314	.00245	.00191	.00150	.00118	.000950	.000760	.000622
	.00694	.00689	.00675	.00653	.00625	.00592	.00556	.00519	.00480	.00445	.00409	.00346	.00294	.00250	.00213	.00184	.00159	.00139
	0°	4°25′	8°45′	13° 0′	17° 5′	21° 0′	24°45′	28°20′	31°35′	34°40′	37°35′	42°40′	47° 5′	50°55′	54°10′	57° 0′	59°25′	61°35′
13′	.00591	.00586	.00571	.00547	.00517	.00481	.00443	.00403	.00366	.00329	.00294	.00234	.00187	.00148	.00119	.000956	.000779	.000638
	.00591	.00588	.00577	.00561	.00541	.00515	.00488	.00458	.00430	.00400	.00371	.00318	.00275	.00235	.00203	.00175	.00153	.00134
	0°	4° 5′	8°10′	12° 5′	15°55′	19°40′	23°10′	26°35′	29°45′	32°45′	35°30′	40°35′	45° 0′	48°50′	52°10′	55° 0′	57°30′	59°45′
14′	.00510	.00507	.00500	.00487	.00472	.00452	.00431	.00408	.00384	.00360	.00338	.00294	.00254	.00220	.00192	.00168	.00147	.00129
	0°	3°50′	7°35′	11°20′	14°55′	18°25′	21°50′	25° 0′	28° 5′	31° 0′	33°40′	38°40′	43° 0′	46°50′	50°10′	53°10′	55°45′	58° 0′
15′	.00444	.00441	.00433	.00419	.00401	.00380	.00355	.00331	.00305	.00280	.00256	.00212	.00174	.00142	.00117	.000958	.000792	.000661
	.00444	.00442	.00437	.00427	.00415	.00400	.00382	.00365	.00346	.00326	.00307	.00271	.00238	.00207	.00183	.00160	.00141	.00125
	0°	3°35′	7°10′	10°35′	14° 0′	17°20′	20°35′	23°40′	26°35′	29°20′	32° 0′	36°50′	41°10′	45° 0′	48°20′	51°20′	54° 0′	56°20′
16′	.00391	.00388	.00382	.00371	.00357	.00340	.00320	.00300	.00279	.00259	.00238	.00200	.00166	.00138	.00115	.000954	.000793	.000665
	.00391	.00389	.00385	.00377	.00367	.00356	.00342	.00327	.00312	.00297	.00281	.00250	.00220	.00195	.00173	.00153	.00135	.00120

To the right of any **height** in the left-hand vertical column, and directly below each **distance** in the top horizontal row will be found a group of three quantities, the upper representing the angle from the vertical at which the point represented by the height and distance under consideration lies; the middle quantity is that by which the candle-power at this angle must be multiplied to give the **Horizontal** illumination at the point under consideration; and the bottom quantity is that by which the candle-power must be multiplied to give the **normal** illumination. **Horizontal** illumination is that received by a surface in a horizontal plane. **Normal** illumination is that upon a surface held perpendicular to a line drawn between the light source and the point under consideration.

In determining the total amount of light given out by a lamp it is necessary to consider the fact that at any angle near the horizontal there are many more beams of a given size than at angles nearer the vertical. This is plainly shown in Fig. 10. That is, each angle represents a belt or zone, and

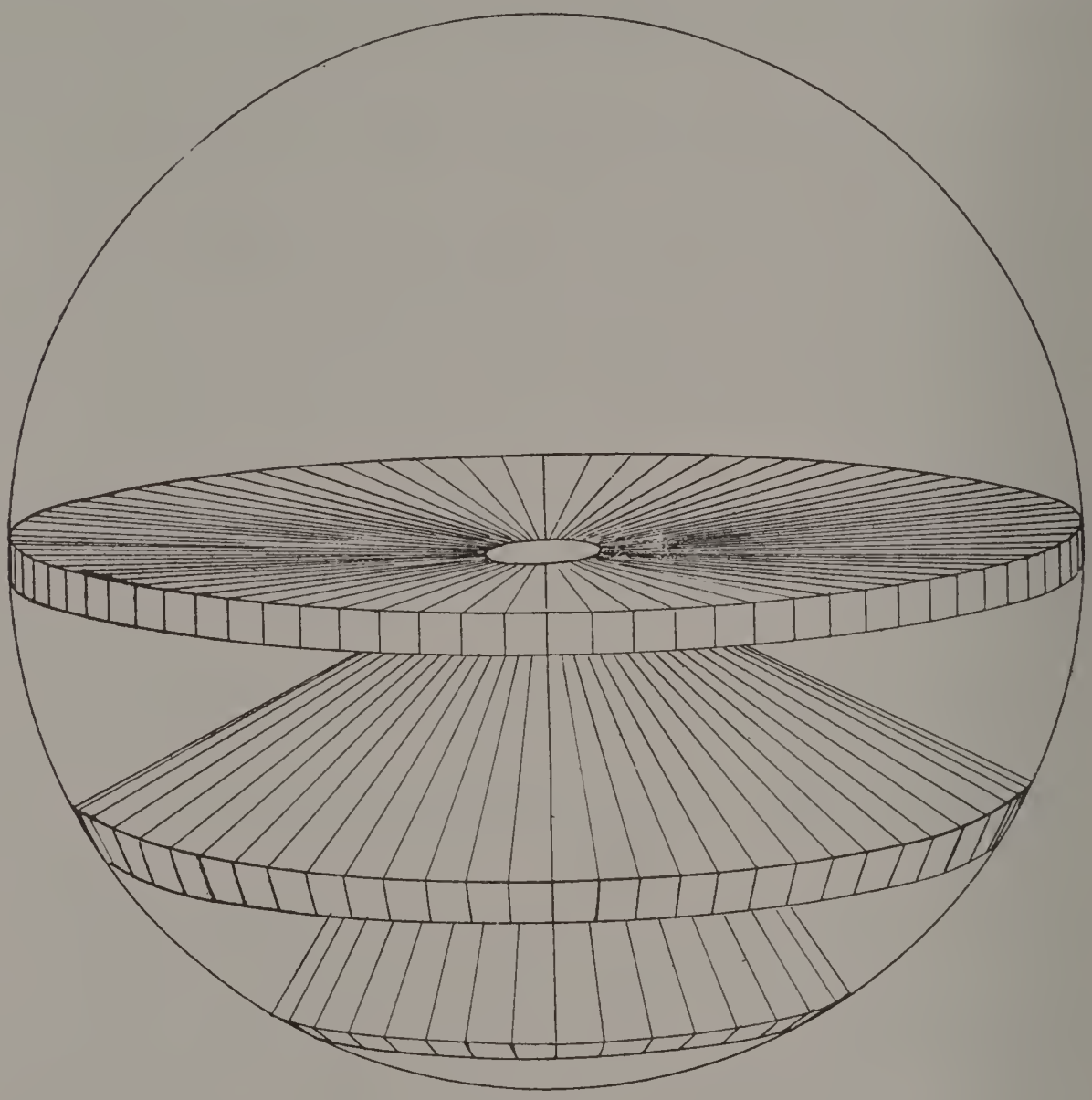


FIG. 10

the area of this belt or zone increases rapidly as the angle increases up to 90°. Beyond 90° the reverse takes place.

By mathematical means which need not be explained here the total quantity of light may be calculated from any *symmetrical* distribution curve, that is, from the curve of a lamp which distributes light in the same way in all vertical planes.

Fig. 11a shows typical non-symmetrical distribution.

Information concerning the total quantity of light, and that in the upper and lower hemispheres, is usually furnished with manufacturers' distribution curves, and there is little necessity for the salesman to make calculations of this sort.

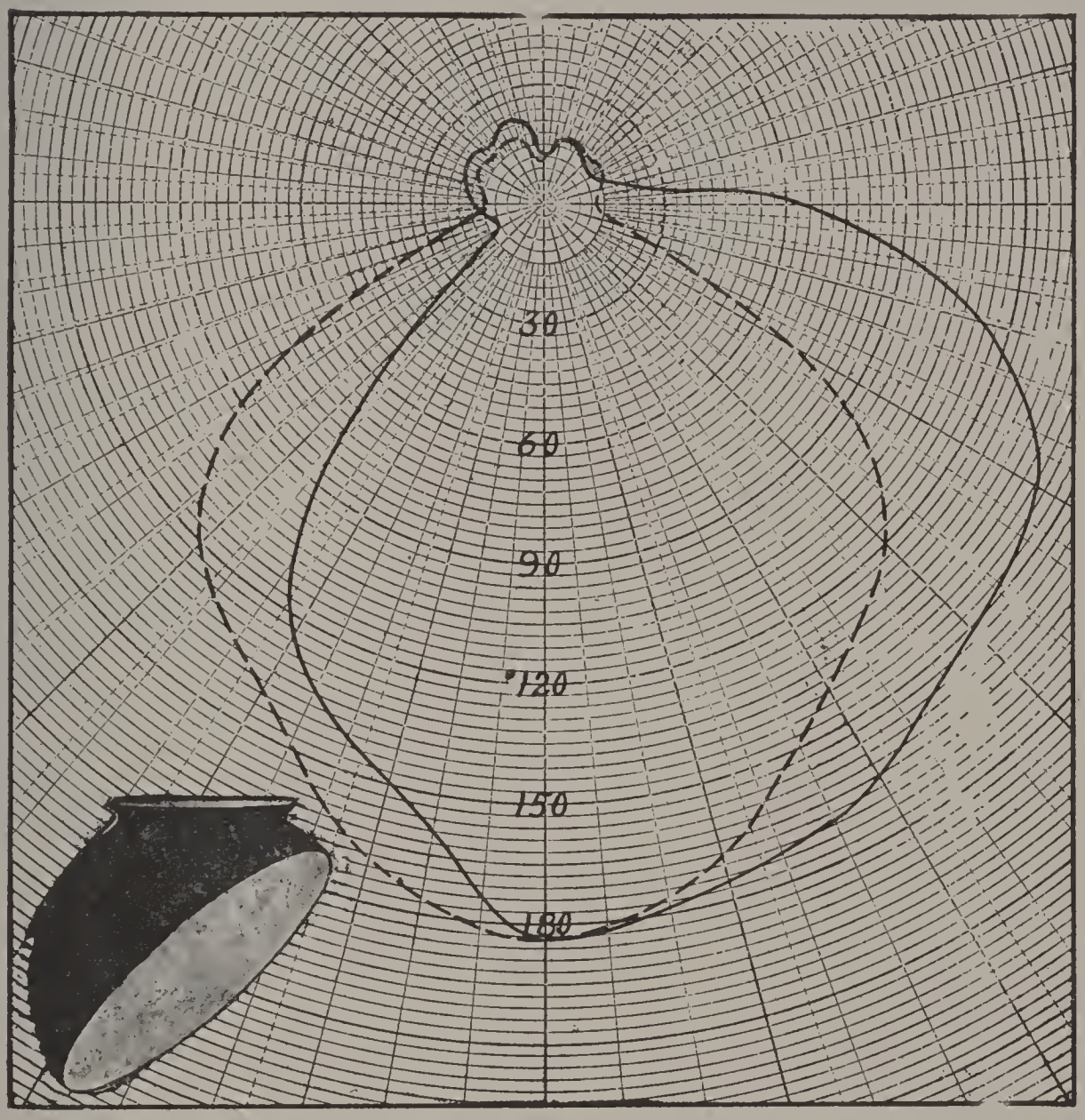


Fig. 11a.

Full and dotted lines show distributions in two vertical planes at right angles to each other.

Without explaining the mathematical basis of these calculations, it may be well to give the necessary rules for calculating the quantity of light in any zone from any lamp, which is as follows:

To obtain the amount of light in any zone 10° wide (extending 5° on either side of any angle), multiply the quantity of light in a beam of standard size at that angle by the factor in the table below:

Angle	Zone Extending From	To	Factor
0° or 180°	0°	*5°	.0240
	175°	180°*	
10° or 170°	5°	15°	.1900
	165°	175°	
20° or 160°	15°	25°	.3860
	155°	165°	
30° or 150°	25°	35°	.5940
	145°	155°	
40° or 140°	35°	45°	.7190
	135°	145°	
50° or 130°	45°	55°	.8600
	125°	135°	
60° or 120°	55°	65°	.9550
	115°	125°	
70° or 110°	65°	75°	1.0300
	105°	115°	
80° or 100°	75°	85°	1.0700
	95°	105°	
90°	85°	95°	1.0900

After calculating the quantity of light in each zone, add together to obtain the total up to any desired angle.

*Since the zone extending 5° to either side of 0° is embraced by a zone 5° wide, the latter must be used at this point.

For instance, to obtain the total light up to 90°, add the results for the following angles 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and one-half that for 90° (since the 90° calculation includes all light from 85° to 95°).

In order to eliminate the necessity of making these calculations the curves shown in Fig. 11 have been prepared. On the right hand is shown the ordinary distribution curve from an opaline reflector of the extensive type and also a dotted curve showing the *ideal* extensive distribution to obtain uniform illumination on both floor and walls with lamps spaced a distance apart equal to twice their height above the floor. On the left-hand side is shown a curve (A) in which the reading of the curve at any angle, according to the scale shown, gives the total quantity of light in a zone 10° wide, 5° to each side of the designated angle. On the left-hand side is also a curve (B) which at any angle shows the total quantity of light from 0° up to and including the designated angle. Thus at 90° is shown the total light below the horizontal and at 180° the total light from the lamp. Comparing the left-hand curve (A) with the ordinary distribution curve of the same lamp shown on the right a great difference will be noted. This is due to the fact that the left-hand curve is what may be called a *plane* distribution curve, showing the quantity of light in one vertical plane only. It does not show all the light emitted, but only that in the direction of a vertical band (Fig. 7) encircling the lamp, while the right-hand curve shows all the light given by the lamp at any angle. The latter, therefore, gives a much better idea of the manner in which the light is distributed than the former. It is seen that even though at any one horizontal direction the quantity of light appears from Fig. 11—left hand—to be quite small, that really a very large proportion of the total light is given out in horizontal directions.

Note particularly that while, according to curve C, most of the light appears to be distributed *below* 60° from the vertical (usually regarded as the "useful zone"). In reality nearly one-half of the light is given out *above* this angle.

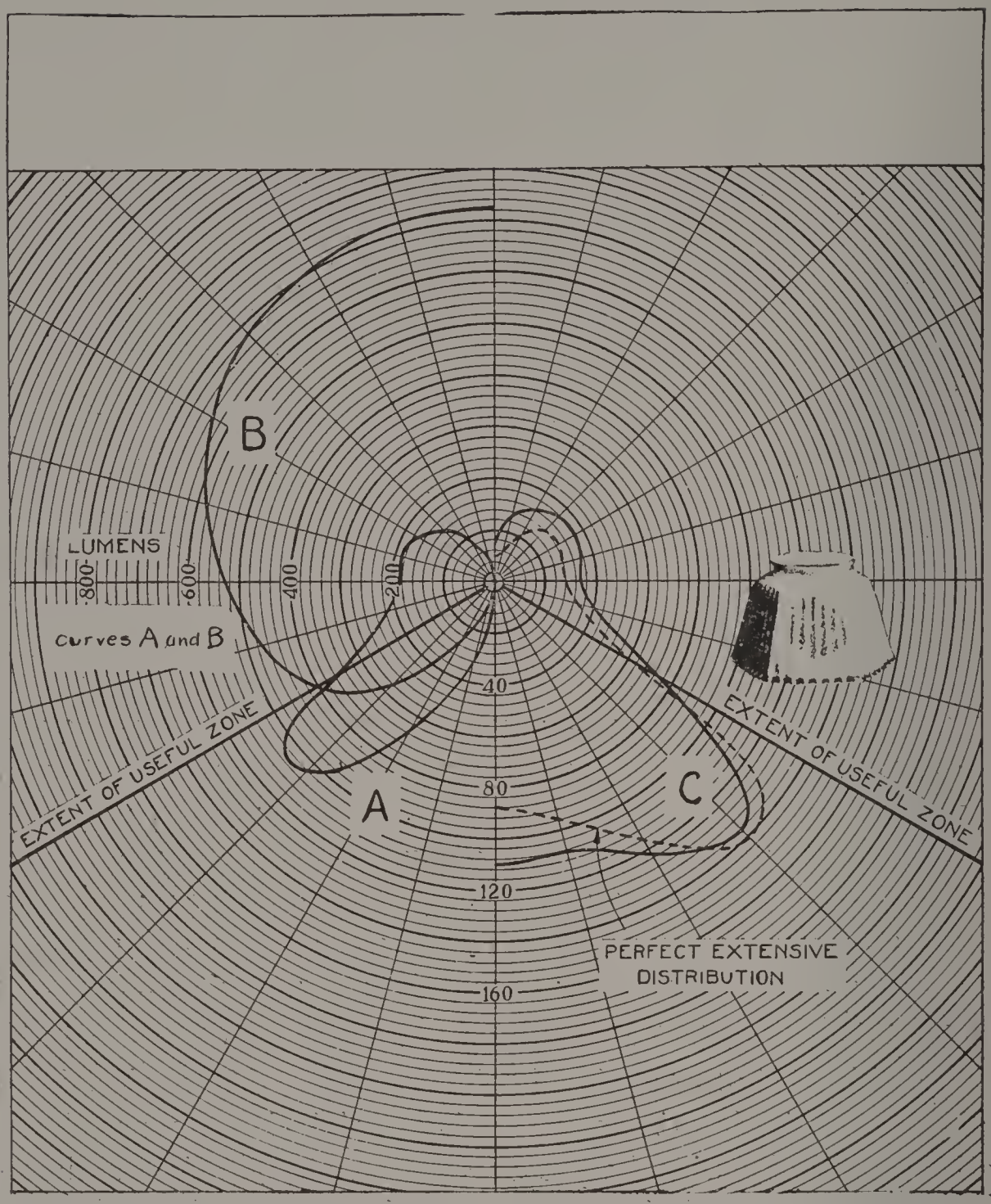


FIG. 11.

After the rays of light leave the lamp they will travel in straight lines and the quantity of light will not be diminished unless some substance exerting a modifying influence is encountered.

The quantity, direction and color of light may be modified in the following ways:

Absorption, by which the quantity of light is diminished

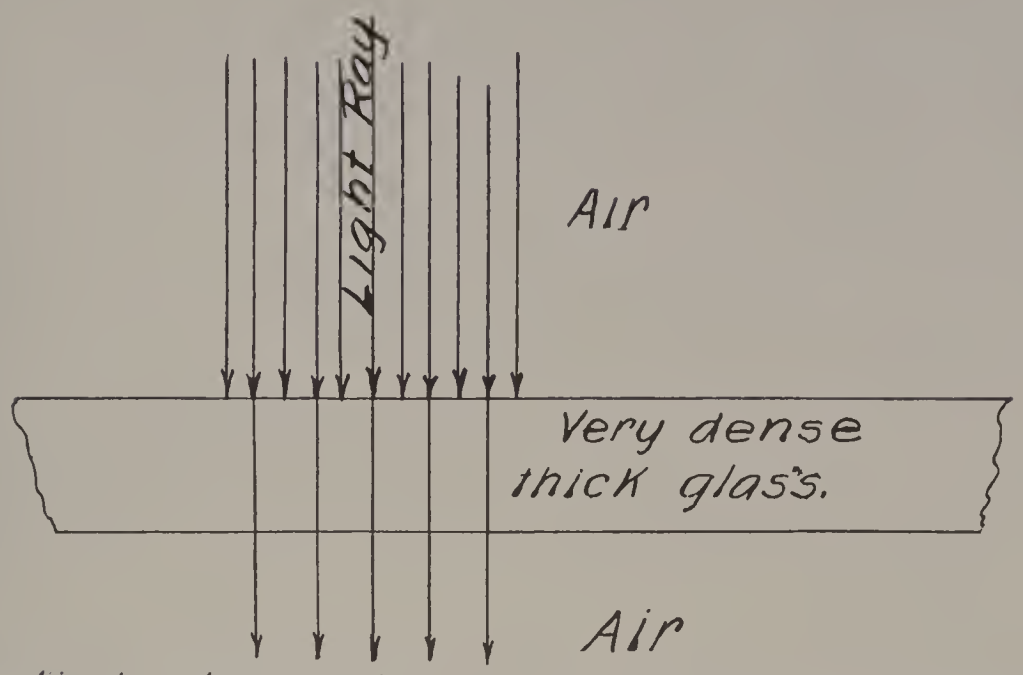


FIG. 12

(partial absorption, Fig. 12) or totally absorbed (Fig. 13). Absorption may or may not affect the *color* of the light. Where absorption is only partial, there is also some transmission or reflection.

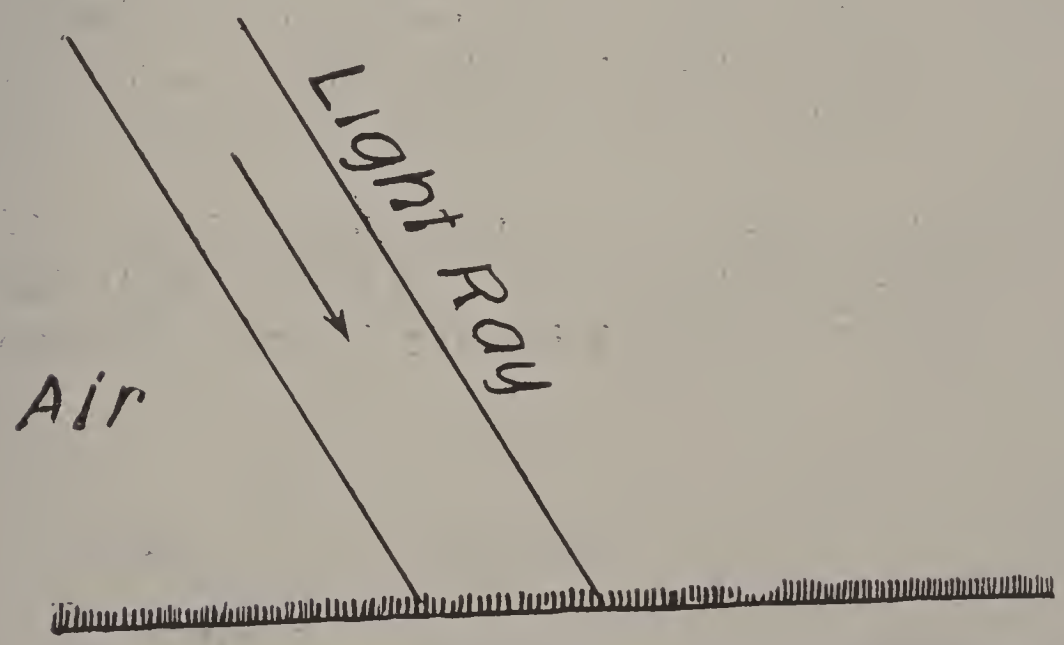
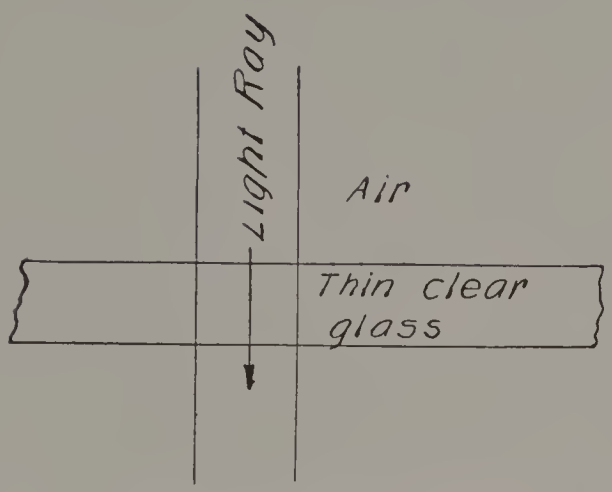
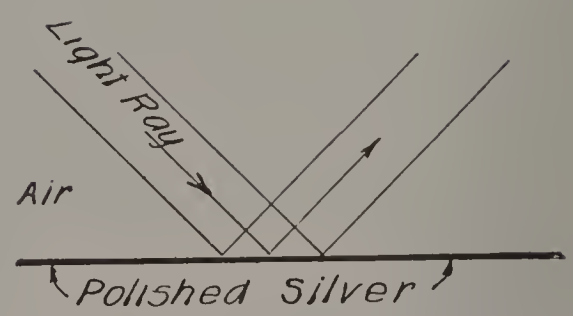


FIG. 13



Total Transmition

FIG. 14



Total regular reflection.

FIG. 15

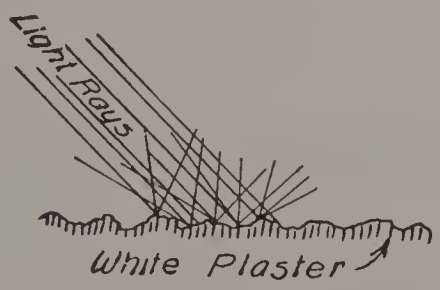
Transmission (Fig. 14)—the reverse of absorption.

Reflection, by which the direction is altered, the light not penetrating beneath the surface of the substance.

Reflection may be either *regular* (Fig. 15) or *diffuse* (Fig. 16). Regularly reflected light rays always leave the surface at the same angle at which they strike it. Diffuse reflection is simply a number of regular reflections from small surfaces at different angles or *not* in the same plane.

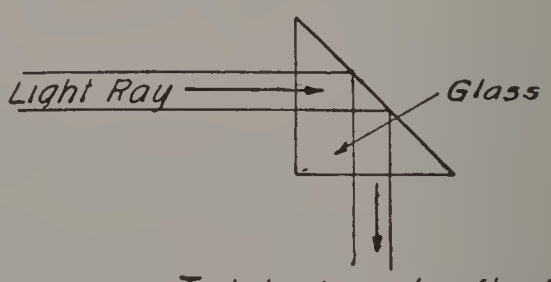
Refraction (Fig. 17), by which the direction of the ray is altered by passing from a transparent medium of one density into one of another density (air to glass, glass to air, etc.). The angle of refraction depends upon the relative densities of the substances.

If in attempting to pass from a denser into a lighter substance, the light rays strike the surface at such an angle that refraction directs the light back into the denser medium, no



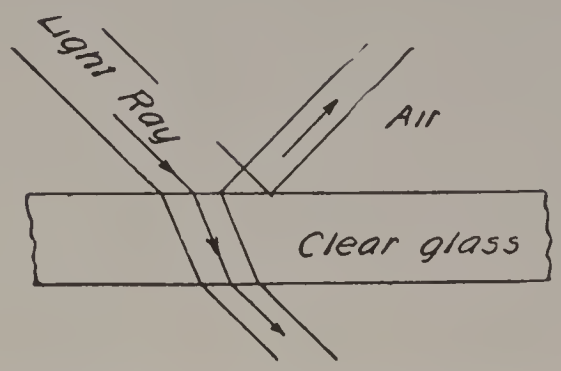
Partial diffuse reflection & absorption.

FIG. 16.



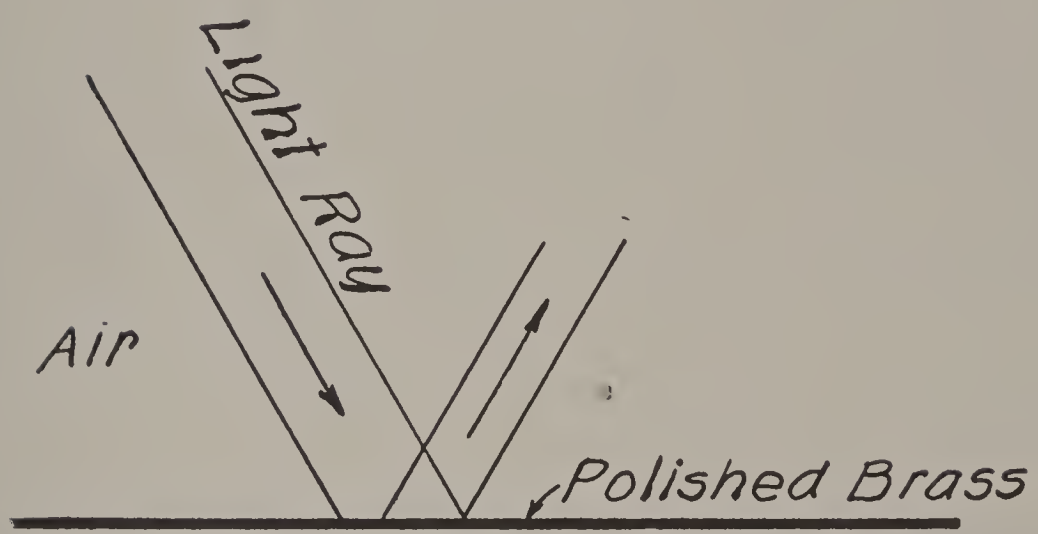
Total internal reflection

FIG 18

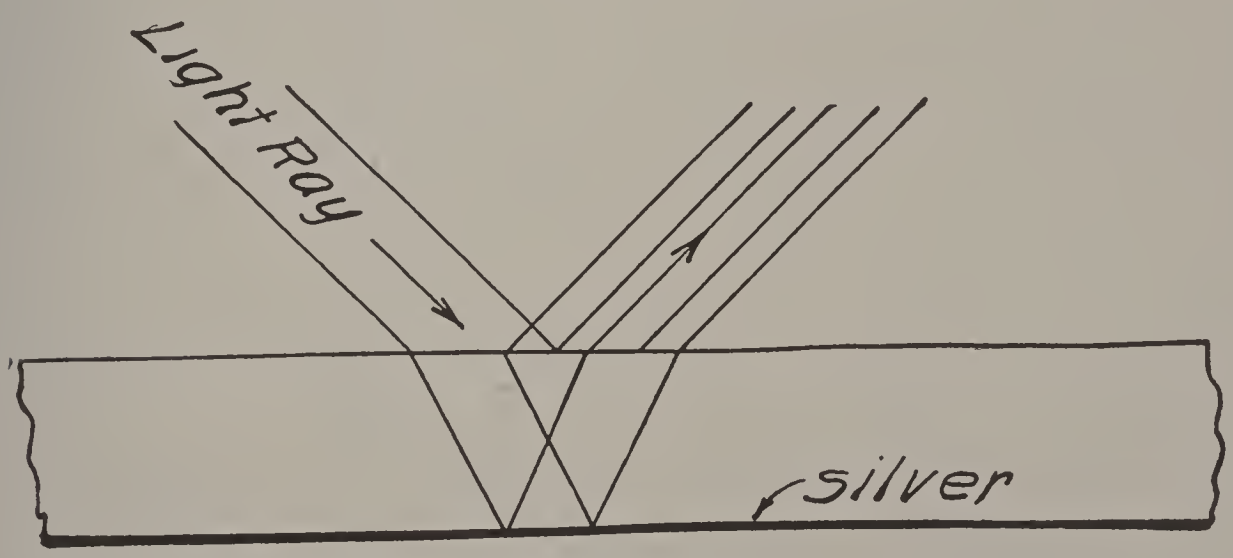


Refraction with partial regular reflection

FIG. 17.



Partial absorption and regular reflection



Refraction with partial regular reflection & total regular reflection.

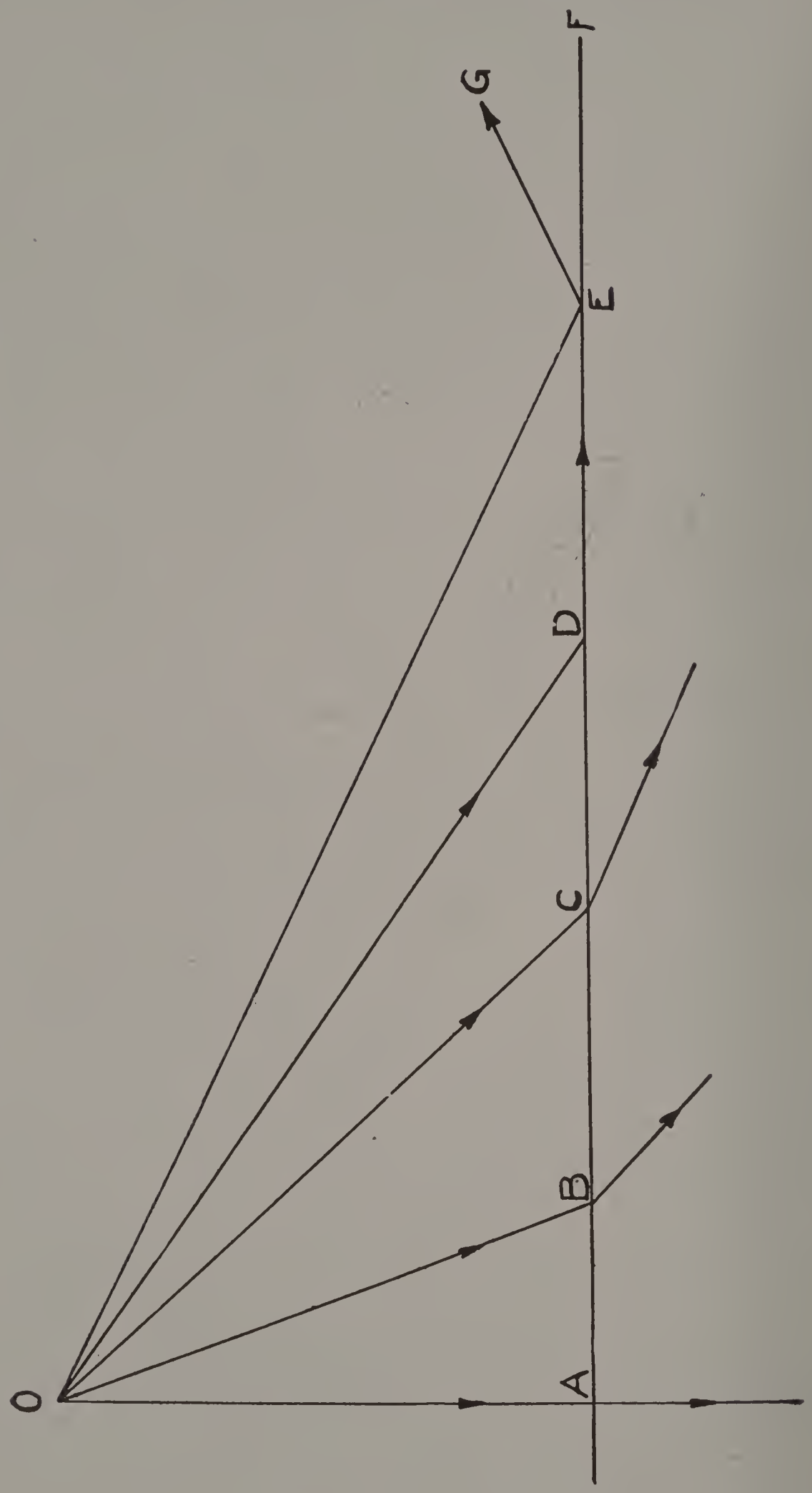


FIG. 18A.

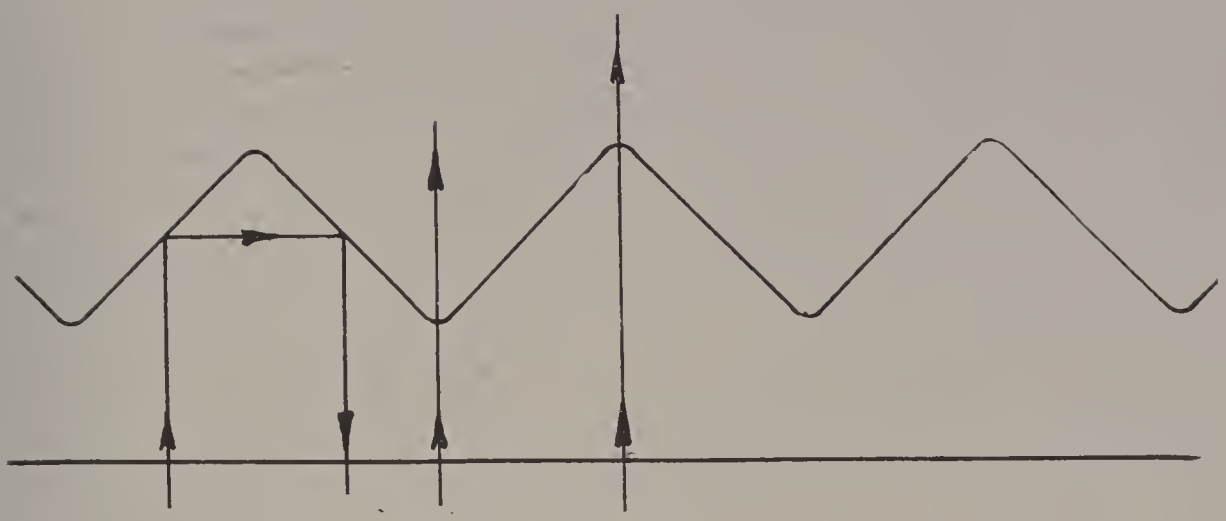


FIG. 19.

light escapes and total internal reflection is said to take place (Fig. 18). The "critical angle" at which this occurs is illustrated by OEG (Fig. 18a).

The action of prismatic glass reflectors depends upon this principle (Fig. 19).

As stated before, the eye perceives objects and their details largely through such contrasts of brightness as result from the form, texture, etc., of the object.

While the subject of reflection may be regarded as of rather academic interest, it is worth while to note the application of a few principles to reflector design.

Figs. 20, 21 and 22 show the type of reflection from polished aluminum, frosted aluminum, and white enameled steel, respectively.

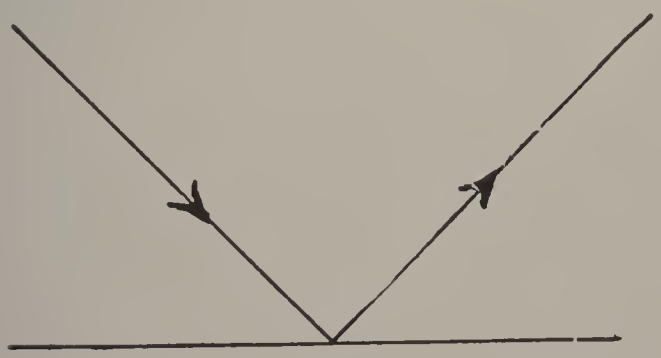


FIG. 20

FIG. 21

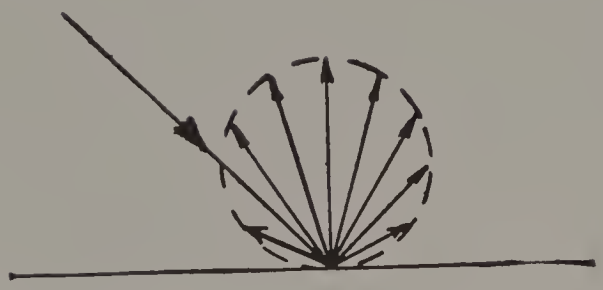


FIG. 22

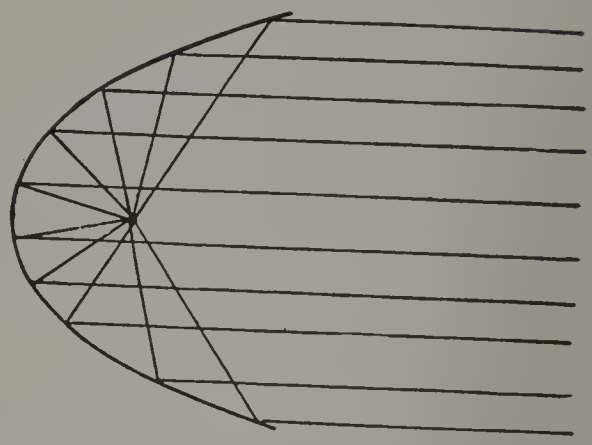
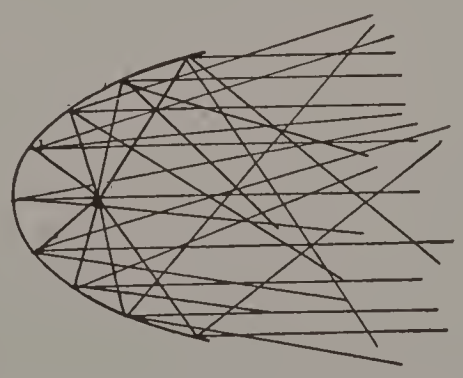


FIG. 23

It is evident from Fig. 20 that all the light in any ray may be redirected in any desired direction by arranging the reflecting surface in the proper position with relation to it. Thus, if desired to direct all the light in one direction in a very narrow beam (as in a search-light), the reflector may be formed as in Fig. 23. Therefore, reflectors of this character are always made of polished metal or silvered glass.

This result may be accomplished to a less extent by the use of frosted aluminum, because of the considerable proportion of regular reflection present (Fig. 21). It is quite apparent, however, that very little control over the direction of the redirected rays may be secured by the use of enameled surfaces. No matter what their shape, all that they can accomplish is to reflect back a portion of the light in the general direction of the open side of the reflector (Fig. 24). They are therefore use-



Diffusely reflecting surface.

FIG. 24.

less for any purpose demanding any considerable degree of light concentration.

Most of the glass reflectors used for commercial lighting combine both regular and diffuse reflection which diffuse transmission. They thus afford some (and in many cases considerable) control over the distribution of light.

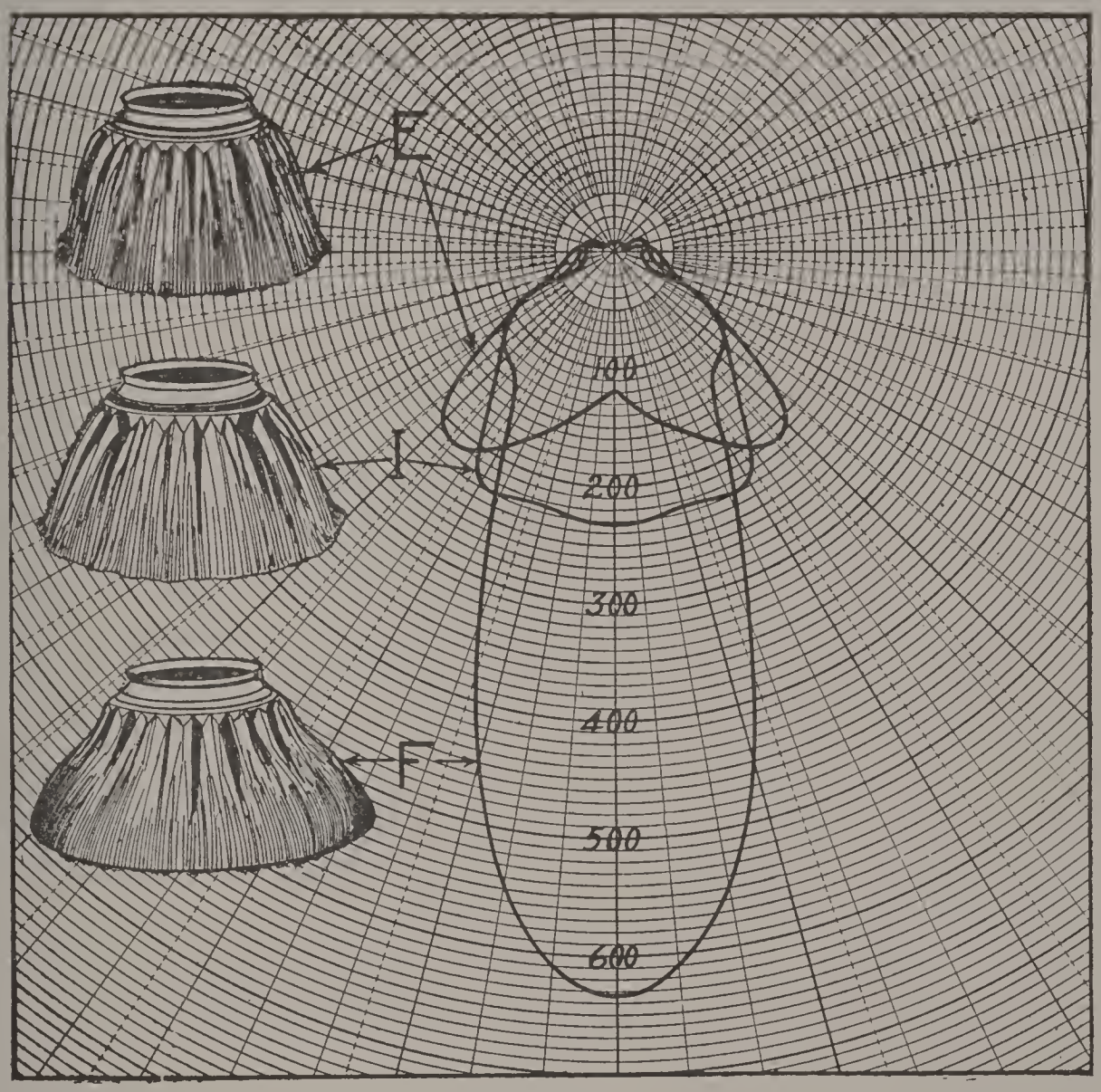


FIG. 26.

Those which act as efficient reflectors, however, are usually lacking in transmission, and do not provide sufficient light at and above the horizontal (Fig. 26) to make their indiscriminate use advisable with gas lamps. In the case of electric lamps placed a very short distance below the ceiling, this deficiency is less objectionable.

Ball globes (Fig. 28), on the other hand, furnish many more times the wall and ceiling illumination than is ordinarily necessary, or even desirable, and do not distribute the light advantageously in the lower part of the room, where it is usually most needed.

The amount of light absorbed by reflecting surfaces (either the equipment of the lamps themselves or the walls and ceilings of the room) depends upon the nature and color of the surfaces. It is impossible to make any estimate of this quality from the appearances of the surfaces.

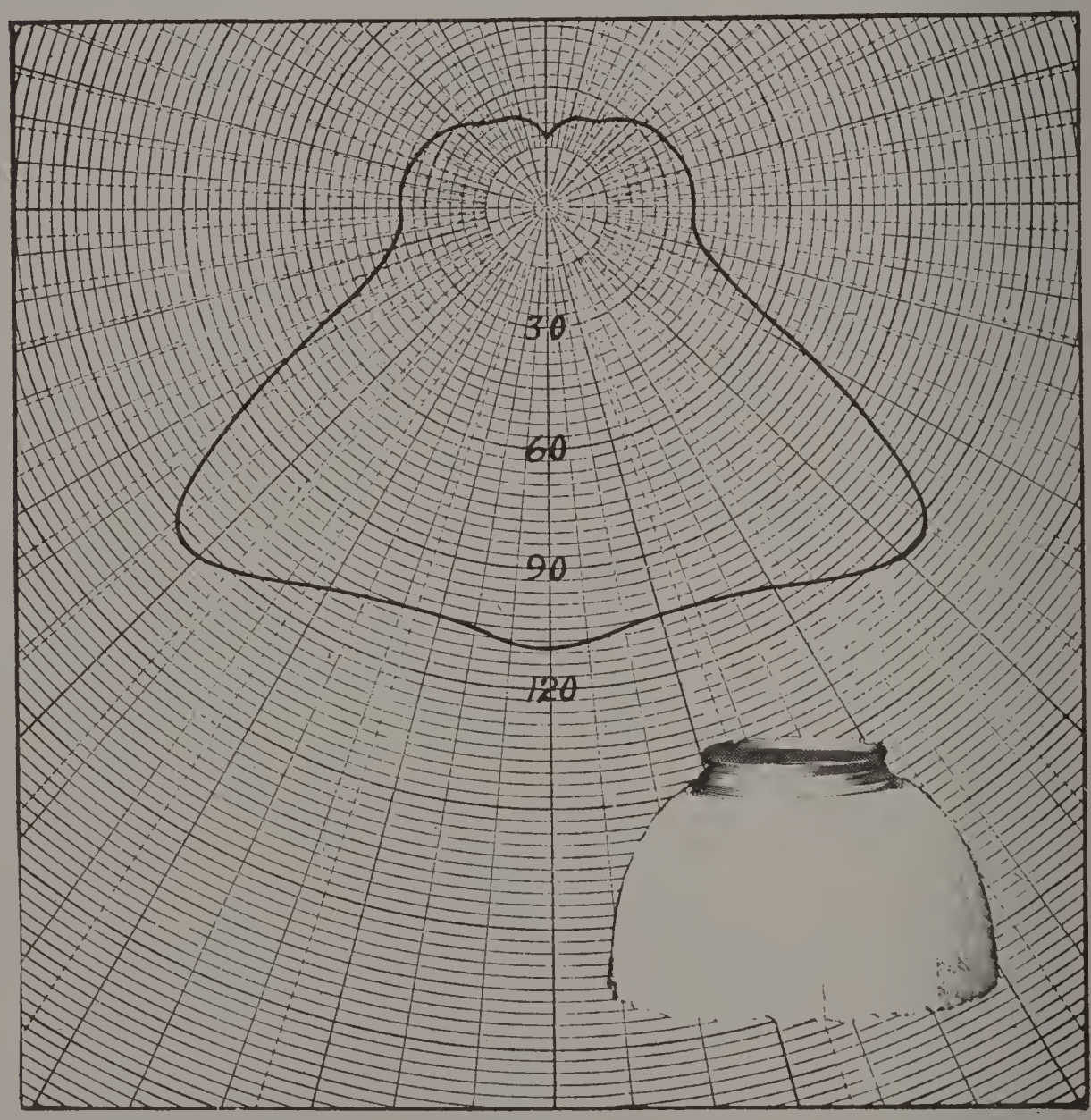


FIG. 27.

The following table gives the proportion of light falling upon them absorbed by various surfaces:

Material	Percentage of Light Absorbed
Polished silver	7 to 8%
Silvered mirror	12 to 18%
White blotting paper	18%
White cartridge paper	20%
Polished brass	25 to 30%
Mirror backed with amalgam	30%
Yellow wall paper	60%
Light blue cardboard	75%
Dark brown paper	87%
Vermilion paper	88%
Black velvet	99.6%

Note the small difference in absorption between white paper and a silvered mirror, and between dark brown and vermilion paper—quite the opposite result from what one would anticipate. Observe also the enormous difference between white and light blue cardboard. It is quite evident that estimates of the effects of light and dark walls upon illumination are very much a matter of guesswork, unless the color and shade be rather precisely stated.

The most important calculations in illumination deal with the light after it has left the lamp.

The salesman must choose from a comparatively small number of lamps and shades in planning lighting installations, and these have fixed characteristics which he is not able to control. He is less interested in how the light is produced and reflected or diffused from the globe or shade than in the effect it will produce upon objects on which it falls.

For most purposes the excellence of illumination is regarded as depending largely (though not entirely) upon the intensity of illumination on the "working plane," which is the plane containing the objects requiring illumination—the tops of desks or tables in office-lighting, the walls in an art-store, etc. There are really six "working planes" in most cases—the floor (or a

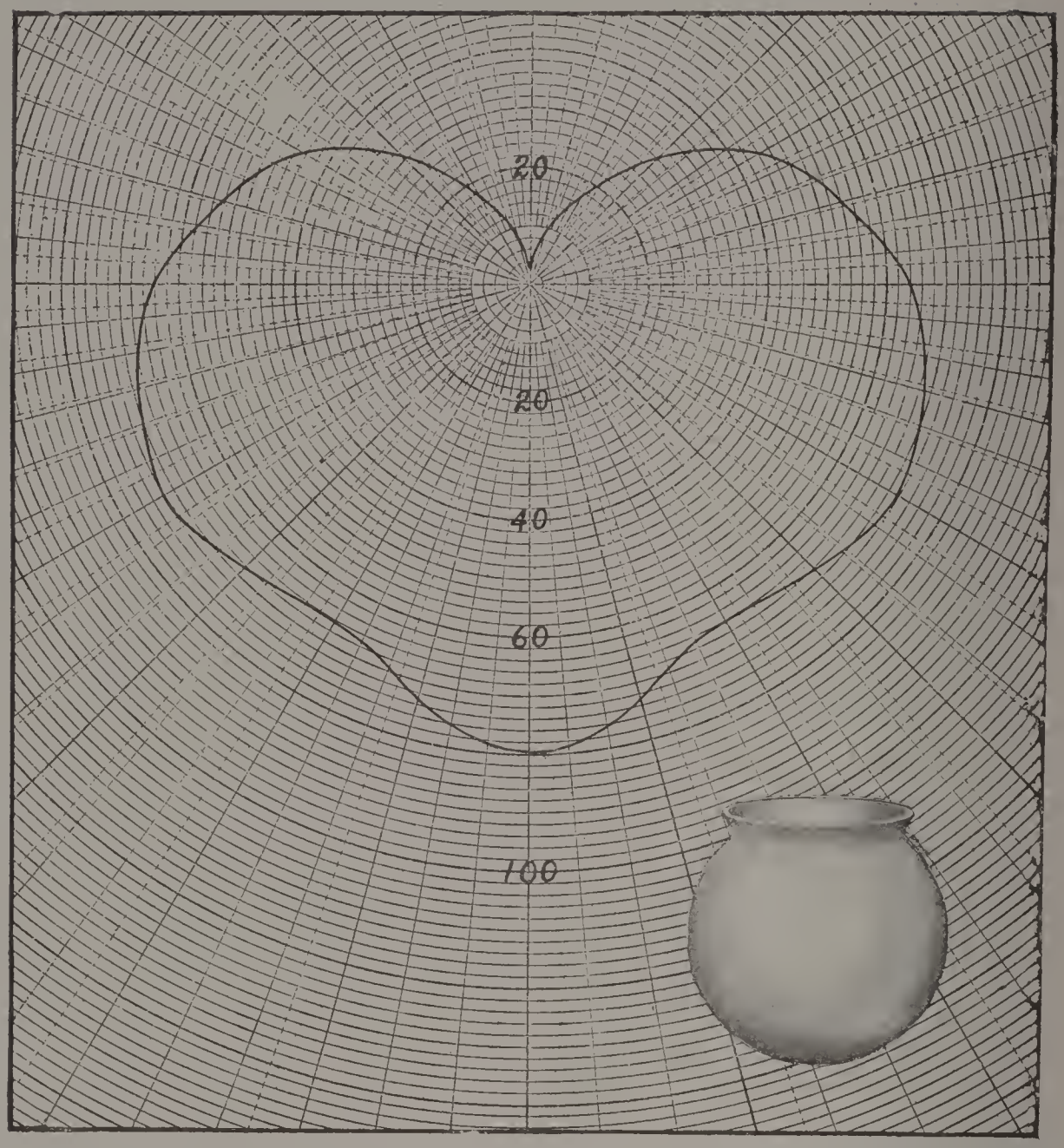


FIG. 28.

certain distance above it), ceiling and four walls. Since separate calculations in these six planes would entail an amount of labor out of all proportion to their value, and in most cases a horizontal plane (usually about 30 inches above the floor) is the most important, manufacturers have designed their commercial reflectors for uniform and efficient illumination of a horizontal plane. At the same time, sufficient light is provided near and above the horizontal to furnish adequate illumination of walls and ceiling for all purposes except where these form the most important planes for illumination. These

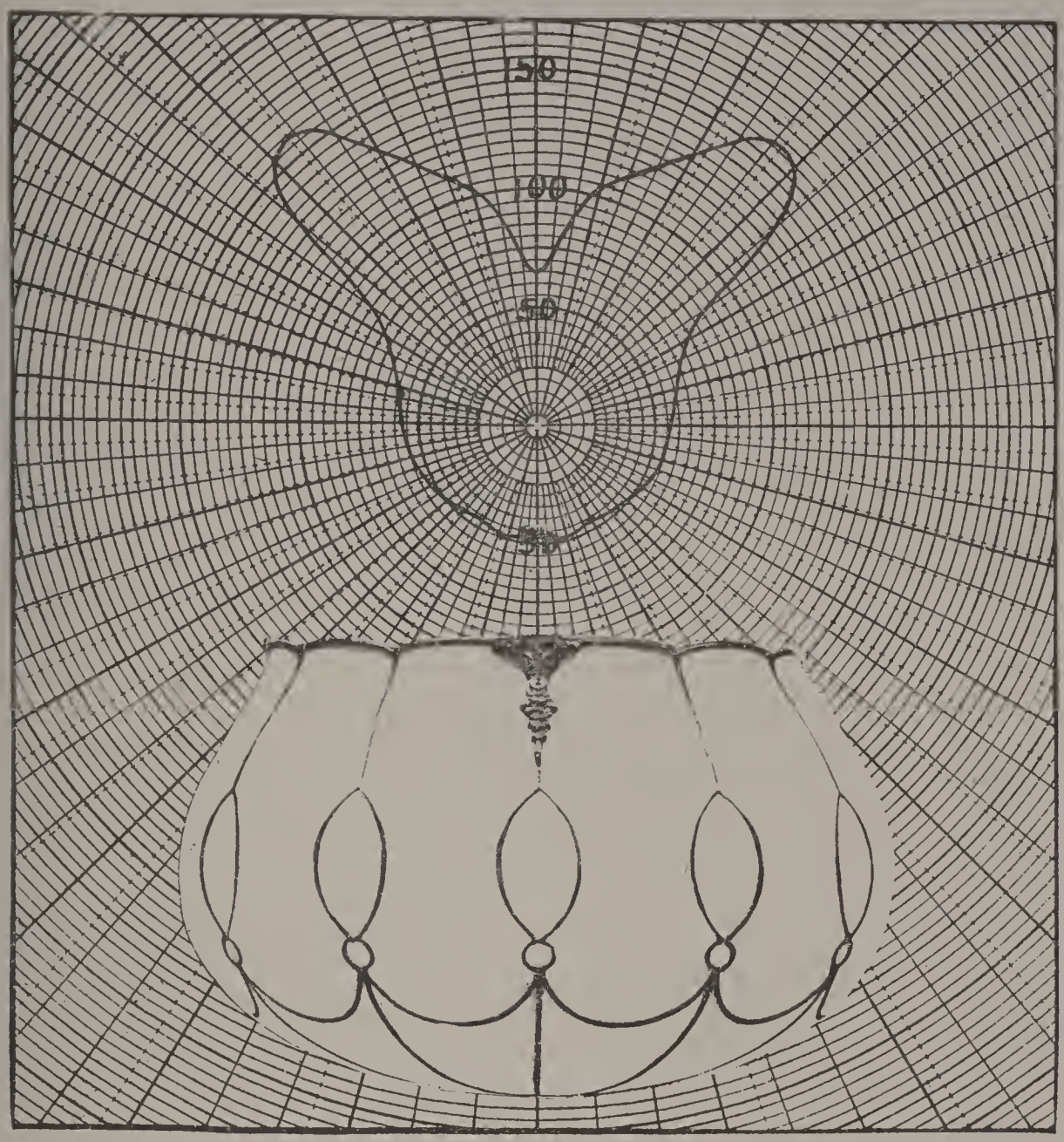


FIG. 29.

exceptions are very few and the salesman, unless he be a specialist, is most unlikely to encounter them.

Provided anything approaching ordinary good judgment is used in the choice of reflectors the salesman will accomplish the best results by basing calculations upon the illumination of the horizontal plane. For this purpose, he may employ either or both of two methods. The first, or "Point-by-Point Method," involves the calculation of illumination at various points in the "working plane" by the method described on page 41. The results of these calculations are often shown in the form of illumination curves (Fig. 25). In these curves,

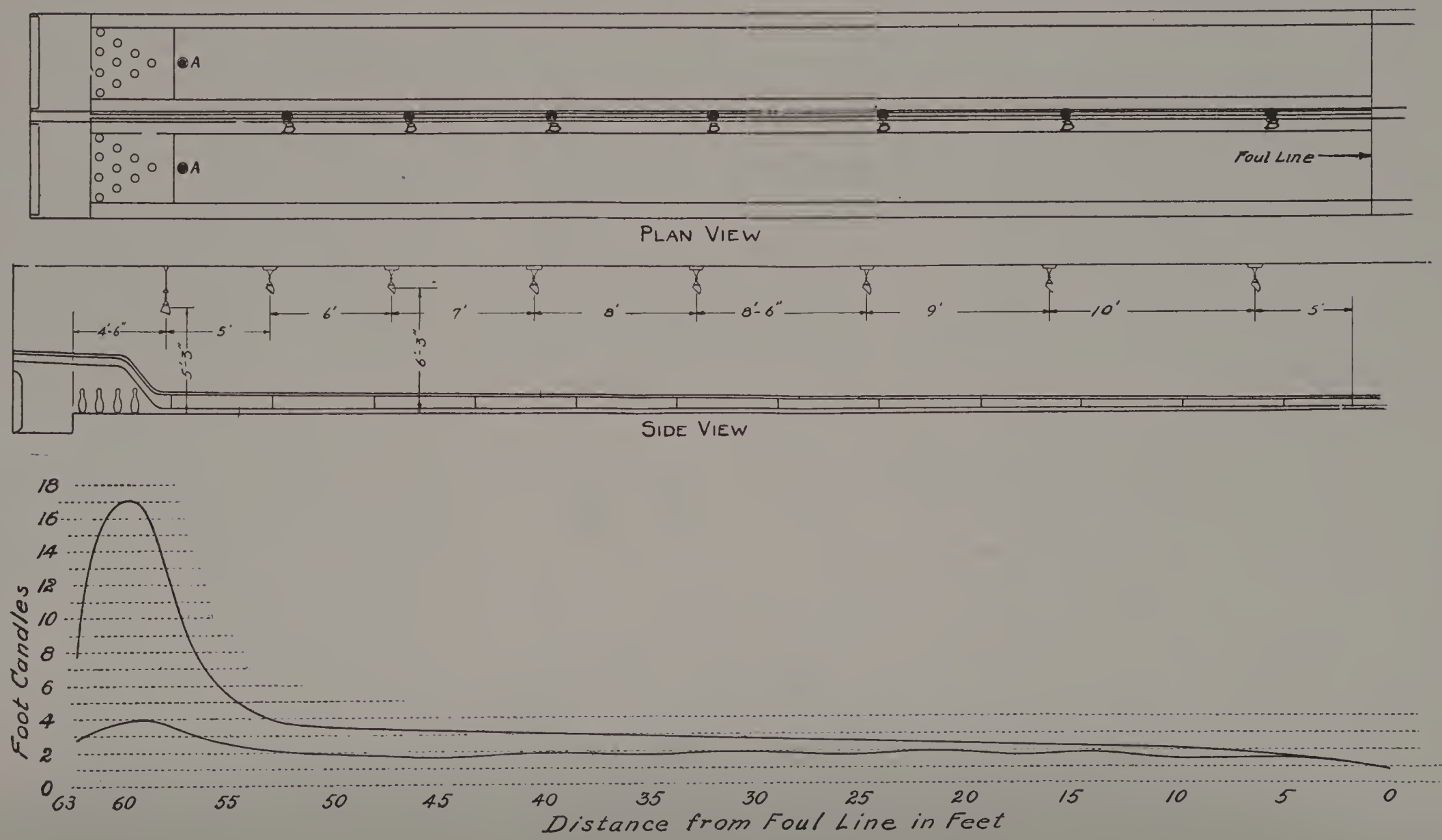


FIG. 25.

Illumination down the middle of a bowling alley. Upper Course—Illumination from 9 small units located as shown. Lower Curve—Illumination from old system.

the base line (A–A) represents a line in the working plane, and the height of the curve above any point in the base line represents, to the scale at the end, the illumination at that point.

Such curves take into consideration the direct light from the lamps only, and disregard that reflected from side-walls and ceiling. Similar curves are also used to show the results of actual measurements of illumination, in which case the light from ceiling and walls is of course included.

That this method is extremely laborious is self-evident.

The second, or "Flux Method," is based upon the results of actual tests in rooms of various shapes and sizes, which have shown that with a given type of lamp and reflector and walls and ceiling of given color, the *percentage* (or proportion) of the total light produced that will reach the horizontal working plane is practically the same in any shape or size of room (within reasonable limits, of course).

From a sufficient number of such tests it is easy to compile a table showing the *percentage* of total light produced which reaches the working plane with various types of reflectors, with walls at various colors.

Such a table follows:

Reflector or Globe	Percentage of Total Light from Bare lamp Reaching Working Plane		Per Cent. Lost by Black Walls
	White Ceiling		
	White Walls	Black Walls	
Clear prismatic reflector (Fig. 26) (E).	65	55	15
Light alabaster reflector (Fig. 27)...	55	45	20
Light alabaster ball globe (Fig. 28)..	50	35	30
Semi-indirect (Fig. 29).....	40	30	25
Indirect (Fig. 30).....	35	25	30

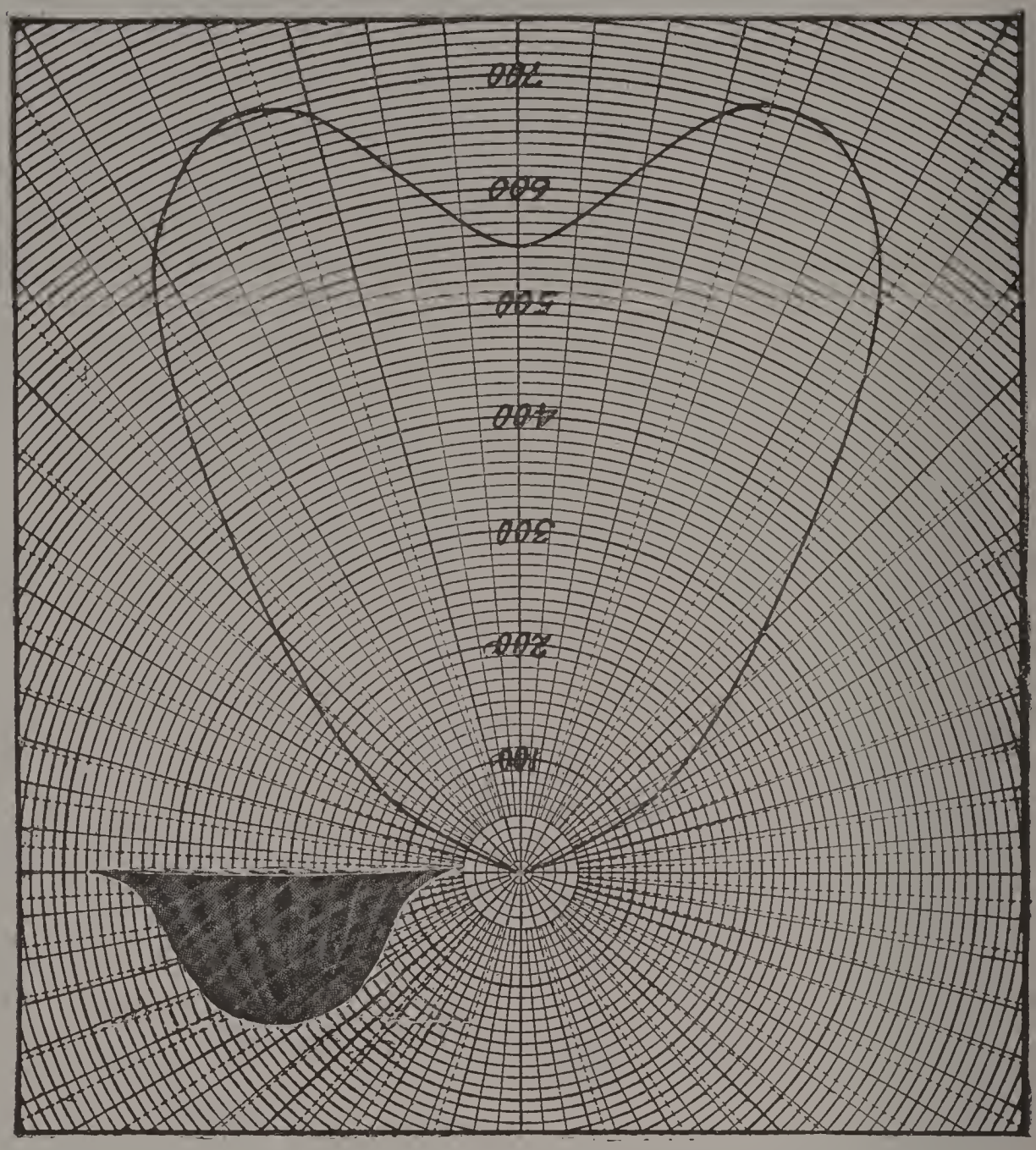


FIG. 30.

These figures are typical only. Globes and reflectors of somewhat different design or quality would give somewhat different results.

Electric lamps will give results differing from gas lamps, since the original distribution of light from the lamp is somewhat different.

For practical purposes, however, they are sufficiently accurate.

As would be expected, dark walls have the least effect where clear prismatic reflectors are used, since a comparatively small proportion of the light is given out near the horizontal. The

ball globe naturally suffers most. The semi-indirect system suffers less than the indirect, since a considerable proportion of the light is sent directly to the working plane.

To use this Table it is necessary first to calculate the total amount of light (in lumens) given by the bare lamps. Multiplying this by the percentage of total light reaching the horizontal working plane gives the total light upon the plane, and dividing by the area of the plane (usually that of the floor) gives the lumens per square foot or the *average* intensity of illumination.

A variation of this method is the tabulation of the total light reaching the working plane from different lamps, instead of percentages. This eliminates the first of the above calculations.

Such a table is shown below:

Single Mantle Inverted Unit (4 cu. ft. per hour size) With	Amount of Light per Lamp Reaching Working Plane	
	White Ceilings	
	White Walls	Black Walls
Clear prismatic reflector	520	440
Alba reflector	440	360
Light alabaster ball globe	400	280
Semi-indirect	320	240

These figures differ somewhat from previously published data on account of changes in mantle and reflector design, which have resulted in changes in light distribution.

Another variation of this method is the tabulation of the amount of light reaching the working plane per cubic foot of gas consumed per hour.

It is not necessary to illustrate this Table, as it is compiled by dividing the figures in the above table by the hourly consumption of the lamp.

Many other modifications of this method may be made to simplify calculations in the design of lighting systems, all of which are based upon the same principles.

This method gives no information as to the *uniformity* of illumination. A room may be lighted to a very high *average* of illumination and yet be very poorly lighted in certain portions. Fig. 31 shows the illumination obtained from two different lamp equipments, giving the same average illumination.

At the point midway between the lamps the illumination from

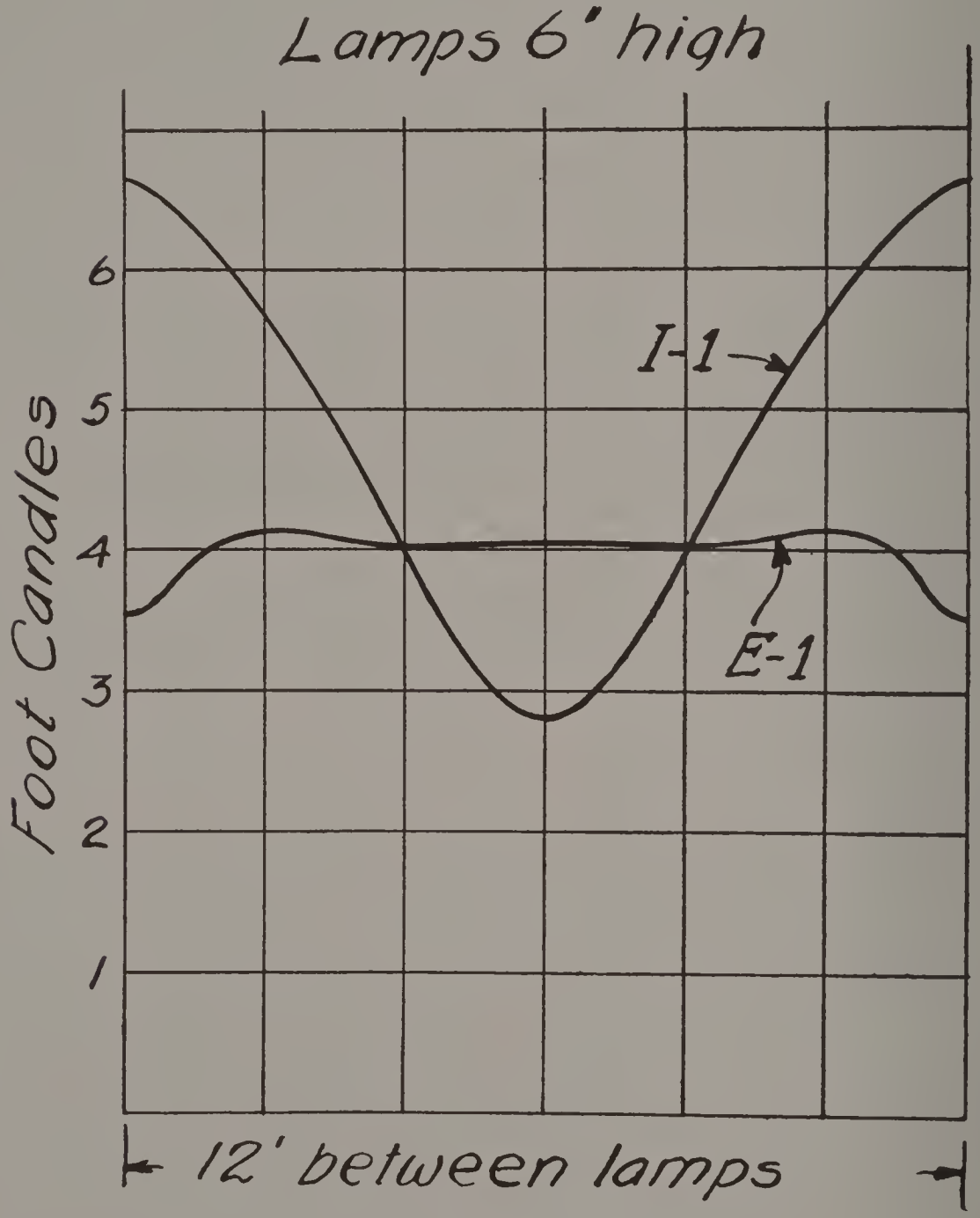


FIG. 31.

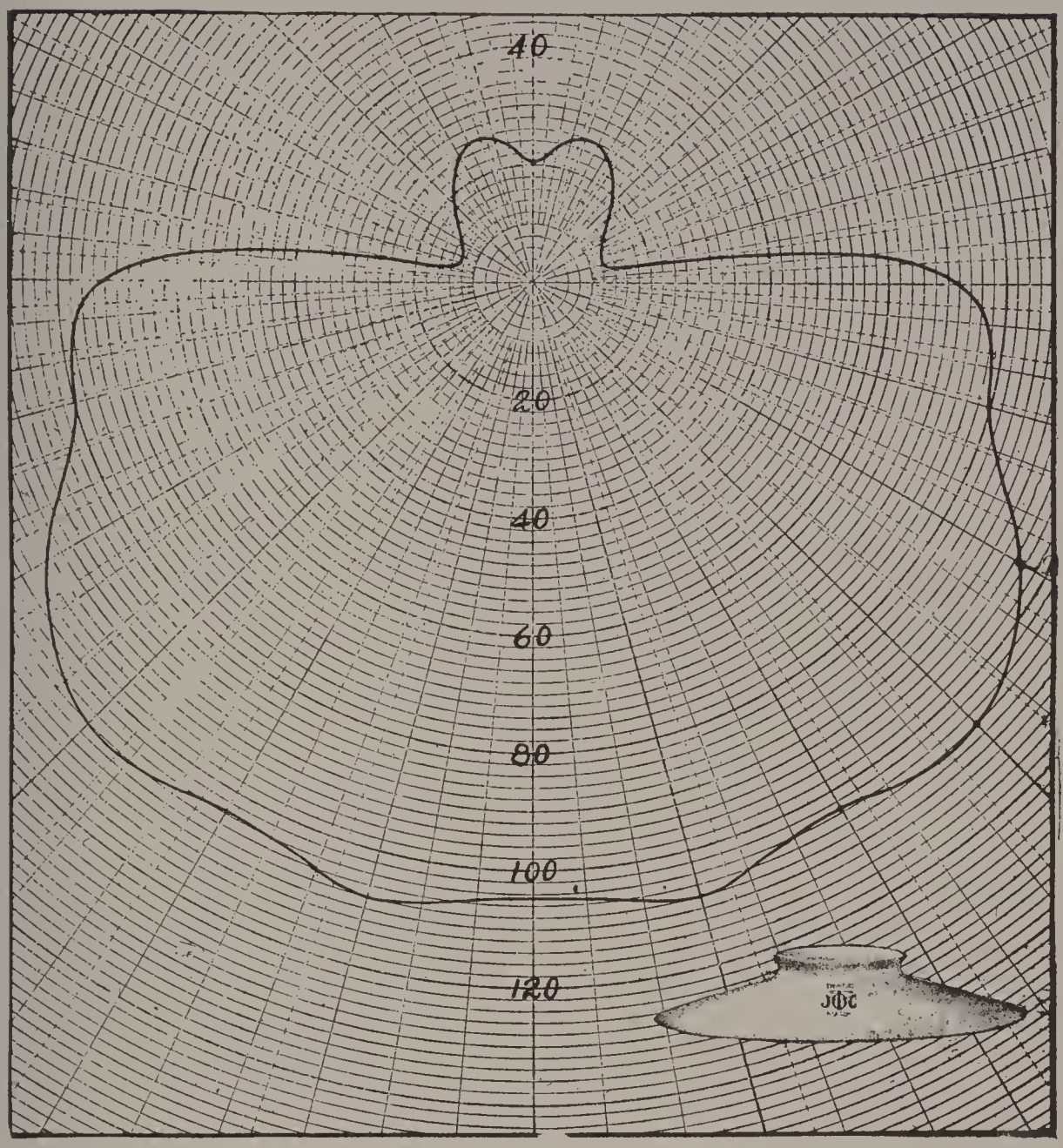


FIG. 32.

one is far below that from the other, though much greater below the lamp. Curve E_1 represents over one-third more *effective* illumination than curve I_1.

Wherever the same sort of work is to be done in all parts of a room, sufficient illumination for the purpose must be provided in *all* portions of the lighted area, and nothing is gained by illuminating any portion to a higher degree than is adequate for the purpose. In the interests of economy, therefore, uniformity of illumination is preferable. In order to assist the salesman in securing this result, reflector manufac-

turers design their product so that certain combinations of reflectors, outlet spacing and lamp, heights (above the working plane) will give the highest uniformity of illumination obtainable.

Fig. 26 shows three types of distribution. Extensive (E) Reflectors will give the most uniform illumination when hung at a distance above the working plane equal to one-half the distance between outlets. Intensive (I) reflectors should be placed at a distance above the plane equal to four-fifths their distance apart, and Focusing (F) Reflectors one and one-third times the distance apart.

Fig. 32 shows a type of distribution having what is loosely termed Distributing Characteristics. It would seem from the name and general appearance that lamps fitted with such equipment might be placed further apart than with the Extensive type.

A little consideration of the principles of illumination laid down on page 40 will show that the reverse is the case.

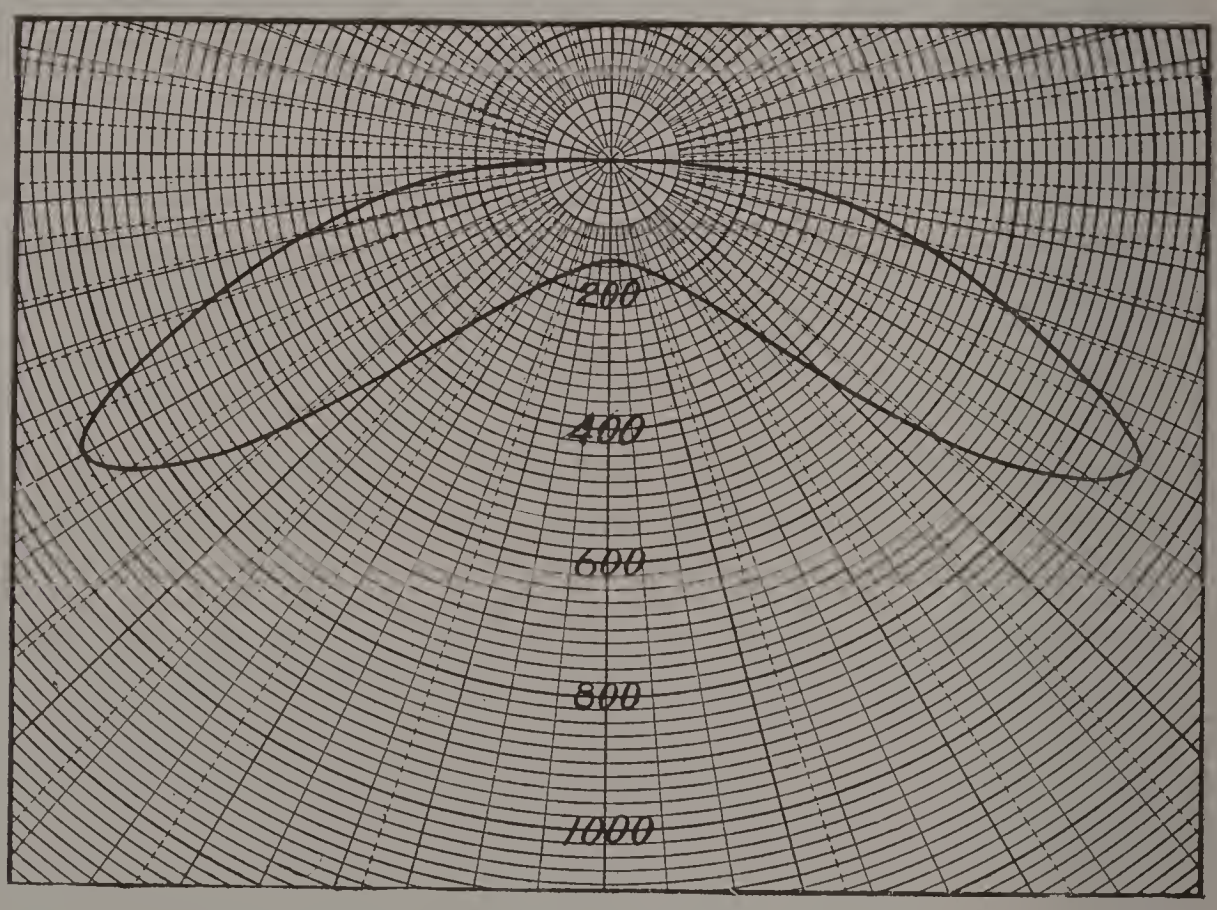


FIG. 33.

As the distance of a horizontal surface from a point directly beneath the lamp increases, its angle of inclination to the light rays, and hence the amount of light required to illuminate it, increase with greater and greater rapidity. Thus, at a point sixteen feet distant from beneath a lamp five feet above the plane, over four times as much light is required as for the same illumination at eight feet distance.

For a reflector to permit wider spacing than with the Extensive type, therefore it would require a distribution somewhat as shown in Fig. 33.

As a matter of fact, Distributing shades and reflectors must be placed closer together than the Extensive type—generally speaking, about one and two-thirds times the height above the plane. That is, the height above the plane should be two-thirds the distance apart.

Generally speaking, with a given type of shade, the closer together the lamps are placed, the more uniform the illumination and the greater the freedom from shadows, especially where walls and ceilings are dark. Light walls and ceilings contribute by diffuse reflection a uniform illumination that tends to reduce the non-uniformity of that received directly from the lamps.

In many cases, however, uniformity of illumination is not the most important consideration, nor is the horizontal plane always the most important one. The character of distribution required will depend upon the class of service and the conditions to be met.

PART III

TABLES

The following tables are typical, but not sufficiently complete for use in the design of appliances. There is also a considerable lack of agreement among the results obtained by different authorities.

Both Specific Heat and Thermal Conductivity vary with the temperature of the substance and its condition, sometimes very widely.

The examples given are intended merely to illustrate the procedure. The calculations required in actual practice are usually much more complicated.

SPECIFIC HEAT

Air (at constant volume)	.16847
Carbon dioxide (at constant volume)	.1535
Oxygen (at constant volume)	.15507
Nitrogen (at constant volume)	.17273
Hydrogen (at constant volume)	2.41226
Water	1.00000
Mercury	.0333
Cast iron	.1298
Copper	.0951
Ice	.5040

To obtain the amount of heat required to raise the temperature of a given quantity of any of the above substances by any amount, multiply the weight in pounds by the increase in temperature and by the figure from the Table.

Example: How much heat will be required to raise ½ lb. of mercury from 32° F. to 50° F.?

$$\tfrac{1}{2} \times (50 - 32 = 18) \times .0333 = .2997 \text{ B. T. U.}$$

THERMAL CONDUCTIVITY AT 0° F.

Air	1.65
Brick	6.00
Asbestos	1.00
Copper	555.00
Cotton wool	1.25
Ground chalk	5.80
Iron	232.00

To obtain the number of B. T. U.'s per hour transmitted through any of the above substances, multiply the area or cross section in sq. ft. of the transmitting material by the difference in temperature in degrees Fahr. between the two sides or ends and by the constant in the above table, and divide the result by the thickness or length in inches.

Example: How much heat per hour will be transmitted through an iron bar 1″ × 2″ (or 1/12′ × 1/6′) in cross section, and 8″ long, having a temperature of 390° F. at one end and 320° F.* at the other?

$1/12 \times 1/6 \times (390 - 320 = 70) \times 232 \div 8 = 28.4$ B. T. U. per hour.

Example: How much heat per hour will be transmitted through a sheet of asbestos 2′ square ($2 \times 2 = 4$′ sq. ft.) and $\frac{1}{8}$″ thick, having a temperature of 350° on one side and 300° on the other?

$4 \times (350 - 300 = 50) \times 1. \div \frac{1}{8} = 1600$ B. T. U.'s per hour.

*The thermal conductivity is assumed constant between 0° F. and 400° F.

MELTING POINT

(The temperature at which the substance changes from solid to liquid form)

	°Fahr.
Carbon dioxide	— 108 (108° *below* zero)
Ice	32
Wax	142 to 154
Tin	446
Lead	620
Copper	1943
Cast Iron	1922 to 2075
Steel	2372 to 2532
Platinum	3110 to 3227

HEAT OF COMBUSTION

B. T. U.'s per pound.

Hydrogen (to water vapor at 212° F.)	60000
Carbon (charcoal)	14500
Carbon Monoxide	4325
Methane (Marsh gas)	23600
Sulphur	4000

GLOSSARY OF TECHNICAL TERMS

CHEMICAL

ATOM.—The smallest portion into which an element may be divided.

COMPOUND.—A combination of elements which may not be separated into its component parts or split up into other substances by physical means (filtering, sifting, etc.), and which possesses properties differing from those of its component parts. (*See Mixture.*)

ELEMENT.—A substance that may not by any known process be divided or split up into other substances.

MIXTURE.—A combination of substances which may be separated into its component parts by physical means (filtering, sifting, crystallization, etc.). (*See Compound.*)

MOLECULE.—The smallest portion of a substance that can exist by itself.

ELECTRICAL

AMPERE.—The unit of electrical current or quantity of electricity, practically defined as that current which will cause the electro-deposition of silver at the rate of .001118 grams per second.

THE KILO-WATT is 1,000 watts.

THE KILO-WATT HOUR is the practical unit of energy, and is represented by the expenditure of 1 Kilo-watt of power for one hour, or at the rate of 10 Kilo-watts per hour for

1-10 hour, or 1-10 Kilo-watt per hour for 10 hours, etc. Thus the Kilo-watt hours are obtained by multiplying the Kilo-watts by the time in hours.

OHM.—The unit of electrical resistance, represented by the resistance at 0° centigrade of a column of pure mercury 106.3 centimeters long, of uniform cross-section and weighing 14.4521 grams.

VOLT.—The unit of electrical pressure of electromotive force (E.M.F.) practically represented by $\frac{1000}{1434}$ of the electromotive force of a standard Clark cell at a temperature if 15° C.

An electromotive force of 1 volt will send 1 ampere through a resistance of one ohm, thus when any two quantities are known, the third may be calculated by the formula:

$$\frac{\text{volts}}{\text{resistance}} = \text{amperes or } \frac{E}{R} = C$$

Where E = E. M. F.
R = Resistance.
C = Current.

THE WATT is the unit of electrical power and is represented by one ampere at an E. M. F. of 1 volt. The watts in in any circuit at any instant are obtained by multiplying the volts by the amperes, that is, amperes X volts = watts or $C \times E = W$, where

W = Watts.
E = E. M. F.
C = Current.

THE WATT-HOUR is the unit of electrical energy and is represented by the expenditure of one watt during one hour. It is $\frac{1}{1000}$ of the kilo-watt-hour.

RELATING TO GAS MANUFACTURE, DISTRIBUTION AND UTILIZATION

MANUFACTURE

CARBONIZATION.—The process of driving off the volatile constituents of coal.

COAL GAS.—Gas produced by heating coal in a closed vessel to a temperature sufficient to drive off its volatile constituents, leaving nothing but carbon (in the form of coke) and ash behind.

GAS CANDLE-POWER is the luminous intensity (measured in candle-power) in a horizontal direction from an Argand burner or (less frequently from the flat side of an open tip burner) consuming 5 cu. ft. of gas per hour, and is obtained by direct comparison with a standard of known intensity. It is an indication of the amount of illuminants in the gas.

HEATING (OR CALORIFIC) VALUE signifies the heating power of the gas expressed in British Thermal Units (B. T. U.'s). One B. T. U. is the quantity of heat required to raise one pound of water one degree Fahrenheit in temperature (from 62° F. to 63° F.), and is obtained by burning a quantity of gas in such a manner that all the heat produced is transmitted to a definite weight of water. By measuring the increase in temperature of the water, multiplying by the weight of the water and dividing by the quantity of gas consumed, the B. T. U.'s per cu. ft. are obtained.

ILLUMINANTS.—Gaseous or liquid constituents of illuminating gas which emit light when burned in an open flame burner.

WATER GAS.—A gas made by decomposing steam by means of incandescent carbon (coal or coke). The oxygen combines with the carbon, forming carbon monoxide (CO), and liberating hydrogen, the resulting gas being mainly a mixture of the two. Water gas is usually *carburetted* by the addition of oils which break up and form illuminants.

DISTRIBUTION

GOVERNOR (PRESSURE).—A device for regulating (or keeping uniform) the gas pressure at the outlet; while the pressure at the inlet varies. Also used for reducing from a high to a low pressure.

PRESSURE (expressed in inches or tenths of an inch) signifies the height of a column of water supported by the pressure of the gas, and is obtained by measuring the *difference* between the levels of a quantity of water in a U-shaped tube, one end of which is connected to the gas supply, the other being open to the air.

SPECIFIC GRAVITY signifies the relative weights of equal volumes of gas and air obtained by weighing equal volumes of each at a given pressure, and dividing the weight of the gas by that of the air.

UTILIZATION

AIR SHUTTER.—In a Bunsen burner, the means provided for varying the size of air-ports.

BUNSEN BURNER.—A gas burner in which a portion of the air required for combustion is mixed with the gas *before* the latter enters the flame.

BUNSEN FLAME.—The flame produced in a Bunsen burner.

ENTRAINMENT.—The sucking in of primary air (by the velocity of the gas) through the air-ports of a Bunsen burner.

MIXING CHAMBER.—The portion of a Bunsen burner provided for the mixing of gas and primary air.

NOZZLE OR TIP.—In a Bunsen burner, the hole through which the mixture of gas and primary air is delivered to the flame.

OPEN FLAME BURNER (also called flat flame, yellow flame, white flame, luminous flame, etc.). A gas burner in which gas is delivered directly into the flame without previous admixture of air.

PRIMARY AIR.—The air mixed with the gas before entering the flame in a Bunsen burner.

ORIFICE.—In a Bunsen burner, the hole through which the gas issues.

SECONDARY AIR.—Air from the outside of the flame in a Bunsen burner.

PHYSICAL

RELATING TO HEAT.

BRITISH THERMAL UNIT. (See under GAS MANUFACTURE.)

LATENT HEAT. The heat required to change a substance from one form into another (solid to liquid, liquid to vapor, etc.) without change of temperature.

SPECIFIC HEAT.—The ratio of the quantity of heat required to increase the temperature of one pound of a substance 1° Fahr. to that required to increase the temperature of 1 pound of water from 62° to 63° Fahr.

THERMAL CONDUCTIVITY.—Capacity for conducting heat, represented by the quantity of heat per hour conducted by a substance through a plate 1 ft. square and 1 inch thick, with a difference of temperature of 1° F. between opposite sides.

RELATING TO LIGHT.

BRIGHTNESS (of a luminous or illuminated surface).—The candle-power given by the surface at a given angle divided by the *apparent* (*not surface*) area. The apparent area of a 6-inch ball globe viewed from any angle is that of a circular area 6 inches in diameter. The apparent area of a flat surface 6 inches square depends upon the angle at which it is viewed and is equal to the surface area multiplied by the sine* of the angle between the surface and the line of vision. From a point directly facing the surface the apparent area is the same as the surface area—$6 \times 6 = 36$ sq. inches. Viewed edgewise,

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* The sine (abbreviated *sin* of an angle is a mathematical constant of the angle. Tables containing sines of all angles will be found in any Engineer's Handbook.

the apparent area is 0; at 30° from the edgewise position the apparent area is $6 \times 6 \times (\text{sine } 30° = .5) = 18$ sq. inches.

CANDLE-POWER.—The unit of solid-angular intensity of emission of light, represented by one lumen per steradian.

FOOT-CANDLE.—The unit of intensity of illumination, represented by one lumen per sq. ft.

INCANDESCENCE.—The state of a body in which it becomes luminous by virtue of its temperature.

LUMEN.—The unit of quantity of light, represented by ten times the amount of light given out in a horizontal direction toward a surface 3 inches square and 30 inches distant from a standard Pentane lamp, corrected to standard atmospheric conditions.

LUMINESCENCE.—The state of a body by which it becomes luminous by virtue of conditions other than its temperature.

STERADIAN.—The unit by which solid angles are measured represented (approximately) by one hundred times the solid angle formed at the apex of a pyramid 1 ft. high and .1 ft. square at the base, or at the apex of a cone 1 ft. high and .01 sq. ft. in area at the base.

RELATING TO MECHANICAL WORK.

ENERGY.—The capacity for doing work. A coiled spring, a moving body, a combustible solid or gas, or a suspended weight possess energy which may be converted into work.

FOOT-POUND (Ft. lb.).—The unit of work, represented by the work done in lifting one pound one foot.

HORSE-POWER.—A unit of Power or rate at which work is done. It is equal to 33,000 ft. lbs. per minute.

HORSE-POWER HOUR.—The amount of work done by the expenditure of one horse-power for one hour.

DUTY.—The amount of energy in one form obtained from a given expenditure of energy or consumption of energy-carrying substance in another form, as horse-power-hours per lb. of steam, candle-power-hours per watt or per cu. ft. of gas, etc.

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